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RE 11th ICAT

Dear ICAT participant:

Thanks to you, the International Network on Appropriate Technology (INAT), held from November 25 to 29, was a success. Over 150 academics and practitioners participated over the five days. The poster competition consisted of 40 quality academic presentations from students and Post-Docs from several countries. Our international keynote speakers came from India, Kenya, Lesotho, the USA, and South Africa.

At each of our 11 International conferences on Appropriate Technology, the highlight is a highly competitive peer review paper competition. The process starts with the submission of abstracts that are blind peer-reviewed. The authors of accepted abstracts received reviews and were allowed to submit full papers. Full papers were double-blind peer-reviewed by 2-4 reviewers. The authors of selected papers revised their papers based on the comments and resubmitted. One of the co-editors of the proceedings was assigned each paper for final review and worked with the authors on any final edits required.

The scientific review committee consisted of over 40 academics and practitioners from 25 different institutions across eight countries. The process started with 75 paper abstracts. After the three-stage review process, we ended with 30 high-quality papers. The authors gave oral presentations and the final papers are included in the conference proceedings with ISBN 978-0-9993666-6-0.

We look forward to your participation in our 12th ICAT in November 2026.
Note: Additional information about INAT and our past conferences can be found on our website (**http://www.appropriatetech.net**).

Sincerely yours,

Gada Kadoda, PhD
Chair, 11th ICAT
Board Member, INAT

John Trimble, Prof.
President, INAT

SECTION: WATER AND SANITATION

Edited by John Tharakan, PhD
Professor, Howard University

THE PRAGMATIC ROLE OF ICTS IN ZIMBABWE RURAL AGRICULTURAL DEVELOPMENT WITH REFERENCE TO CLIMATE CHANGE

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ABSTRACT

Rural communities in Zimbabwe rely mostly on agriculture as their main source of livelihood. The impact of climate change has been observed in rural communities and as a result food insecurity, water scarcity and loss of livestock are beginning to take their toll. Climate change has also reduced the availability of natural resources with land becoming less fertile. This paper envisages the pragmatic role of Information and Communication Technologies (ICTs) in promoting rural agricultural development in Zimbabwe, with a focus on the impact of climate change. The study employs both qualitative and quantitative research methods to investigate the current state of ICT use in rural Zimbabwe. Emphasis is made to investigate the use of ICT in the agricultural sector, as well as the potential benefits and challenges of ICT adoption in mitigating the effects of climate change in agriculture. The findings suggest that the ICTs have the potential to significantly improve not only agricultural production, but also resilience in the face of climate change. However, there are barriers to adoption, such as inadequate infrastructure, limited knowledge and access to financial support. The paper concludes with a set of recommendations for policy makers and stakeholders in the promotion of effective and sustainable use of ICTs in Zimbabwe's rural agricultural development.

Keywords: *Rural agriculture, ICTs, Climate change, Agricultural development, natural resources*

INTRODUCTION

According to Food and Agriculture Organisation (FAO), the agricultural sector is going to face an enormous challenge to feed an estimated global population of 9.6 billion in 2050 (FAO, 2009). Zimbabwe alone is estimated to have an excess of 6 million people by the year 2030. The agricultural industry has an enormous task to supply food for an ever-expanding population. There are two ways the industry can adapt to this pressure, thus intensification and extensification. Extensifying agricultural practices involve clearing out more land and dedicating more resources to agricultural efforts. On the other hand, intensification entails using the resources available and coming up with ways of making them more productive. Extensification is not a probable solution because already there is vast pressure on the land resource which has seen even some farm lands being converted to residential areas. Clearing out more land in general destroys the carbon sinks, thereby accelerating global warming which in turn cause climate change. The effects of extensifying agricultural purposes have led researchers leaning more towards intensification. High production in agriculture can be achieved if the adoption and utilisation of Information Communication Technologies (ICTs) come to precision in a sensible and realistic way that is based on practicality rather that theoretical consideration, a situation that is well described by pragmatism. The purpose of this paper is to investigate the pragmatic role of ICTs in rural agriculture of Zimbabwe. Focus is mostly directed towards information consumption and dissemination to foster agriculture behaviour patterns by farmers in the wake of climate change. The research employs mixed quantitative and qualitative research design methods to explore ICT role in agriculture in line with their adoption and utilisation ICT tools in addition to information consumption and dissemination. Such questions as, current state of ICTs in rural areas, benefits and challenges posed by ICTs and rural farmers' issues about climate change are asked.

RELATED STUDIES

Information Communication Technologies (ICTs) in agriculture

ICTs have penetrated agricultural sector to improve productivity. They include, mobile phones, computers, Internet, telephone, soil moisture tester, TV, storage devices, marketing information systems, Geographical Positioning Systems (GPS) and remote sensory systems. They have been used extensively to improve productivity (Asenso-Okyere and Mekonnen, 2012) especially in commercial farming.

Agriculture plays a significant role in Zimbabwe's economy, contributing approximately 16% to the country's Gross Domestic Product (GDP) and providing employment to over 70% of the population, directly or indirectly as per the Export Busket Index published by Harvard University (2020). Zimbabwe has a total of 33 million hectares of arable land. Zimbabwe has about 7.1 million smallholder and rural farmers occupying a total of 21 million hectares of the 33.3 million hectares used for agricultural purposes. Despite these being the majority of farmers, rural and smallholder farmers occupy areas of lower potential for agriculture in terms of rainfall, soils and water for irrigation. In addition, these areas are of lower economic potential because of the distances from markets with poor communication and infrastructure. To add to farmers wore in these areas, climate change has led to unpredictable weather patterns, soil degradation and water scarcity, making it worse for farmers to keep up and be productive. This has in turn affected food security and the economic development of the country. It is key to note that these farmers constitute the majority of rural Zimbabwe.

Schimmelpfennig, (2011), in his work envisage that, advancement in technology, especially ICTs have seen the term precision agriculture gain popularity. Precision agriculture is a contemporary approach integrating advanced technologies into farming practices to maximise efficiency, productivity and sustainability. This has seen non-traditional agriculture economies improve their agricultural productivity and achieve sustainable agricultural endeavours. Through research, development and implementation of agricultural technologies, desert countries such as Iran are now producing more agricultural produce than countries with ample arable land such as Zimbabwe. This begs the question, are smart agriculture technologies, which are known to use ICTs, the key stone needed to improve not only the rural agricultural development, but also their general livelihoods?

Asenso-Okyere and Mekonnen, (2012) lauded that ICTs can fully optimise productivity and processes of farmers in rural areas resulting in Zimbabwe rural agricultural development attain high productivity, a clear support of Schimmelpfennig, (2011) ideas. As noted in other countries, ICTs have the potential to alleviate some of the challenges facing Zimbabwe's agricultural sector. ICTs have the capabilities to provide farmers with access to information, markets and financial services, as well as facilitating communication and collaboration among stakeholders. The use of ICTs can help smallholder farmers mitigate the effects of climate change by providing real-time weather data, early warning systems and other relevant information so that farmers effect change in agricultural activities. The evolution of the agricultural sector in countries like Israel is a testament to the benefits of ICTs in the agricultural sector and tailor-made solutions for Zimbabwe have the potential to aid these farmers.

Rural agricultural development in Zimbabwe

Most African economies are producers of raw materials. The Global Entrepreneurship Monitor (GEM) classifies these economies as factor-driven economies, where economic development is primarily driven by basic requirements: development of institutions, infrastructure, macroeconomic stability, health and primary education. The main characteristic of such economies is the production of low-value added commodities. This then translate to the main industries being mostly agriculture and mining in Zimbabwe.

Zimbabwe's agricultural demography is divided into two distinct categories, the commercial and subsistence farmer. The commercial farmers own large pieces of land, averaging 200Ha. They produce specifically for the markets. They have the resources to finance their production, and consequently always produce more. The occupy lands of greater potential, in the regions with favourable weather conditions. On the other hand, small scale farmers, or the subsistence farmers produce for their own consumption. The occupy land of lesser nutritional potential, and barely have enough capital to utilise even the land they possess. These farmers constitute the majority of Zimbabweans living in the rural areas. According to the data from the World Bank, of the 32 million hectares, which is the total arable land in Zimbabwe, the subsistence farmers occupy 22 million hectares while the commercial farmers only occupy 11 million hectares (2019). Over the past years, getting as far back as to the years prior to Zimbabwe independence (1980), the commercial farmlands have always been mechanised. Agricultural practices in these areas have always been conservative to maximise profits one way or the other. It is no surprise that these areas are leading in the implementation of ICTs technologies currently to further intensify their productivity. The rural farmers on the other hand have always lagged behind in terms of technology implementation in their areas; and information consumption and dissemination is still a challenge to date.

The Agricultural and Rural Development Authority (ARDA) is a Government of Zimbabwe Parastatal, under the now Ministry of Lands, Agriculture, Fisheries, Water and Rural Development (MLAFWRD), created by an Act of Parliament, The ARDA Act 18:01 of 1982. Their main aim is Rural Development and Industrialisation. They have spearheaded several initiatives to develop rural agriculture in Zimbabwe, which include the establishment of 450 irrigation schemes covering 26 000ha of arable land (ARDA-Strategic-Plan-2021-2025). Most of these schemes are in the rural areas, where communities have formed cooperatives to make use of the developed irrigation schemes. ARDA is the leading governmental stakeholder in rural agriculture development in Zimbabwe.

ARDA has resulted in the awareness of smart agriculture amongst the rural population and the results of its operations are bearing notable fruits.

Overview of ICTs spread in Zimbabwe

In recent years, the use and access to ICTs have expanded significantly in both rural and urban areas, although there are gaps in access and quality especially in developing countries such as Zimbabwe. In urban areas, the spread of ICTs has been faster and more extensive than in rural areas due to factors which include the availability of infrastructure and greater economic resources. Urban areas have higher rates of access to ICTs, including the internet, mobile phones and computers. According to DataReportal, there were 5.74 million internet users in Zimbabwe at the start of 2023, when internet penetration stood at 34.8 percent. However, higher rates are in urban areas as compared to rural areas. The report further stated that at the start of 2023, 32.5 percent of Zimbabwe's population lived in urban centres, while 67.5 percent lived in rural areas. Further, the quality of internet in Zimbabwe still leaves a lot to be desired. In November 2022, Zimbabwe ICT, Postal and Courier Services Minister said that in as much as internet penetration had increased, broadband network extension lagged behind. According to the information presented by the International Telecommunications Union (ITU) during the Digital Innovation Profile Workshop in June 2023, 34% of Zimbabwe has at least 4G network coverage. This is mostly concentrated in the urban areas while the majority of rural population still use 2G. The key providers of Internet in Zimbabwe are the major Mobile Network Operators namely Econet Wireless and Netone. Telone and other Internet Service Providers such as Utande service a small demography, mostly in the urban areas.

ICTs in rural agricultural development and climate change

The first step towards solving any problem is to admit there is a problem (Daniel, Newsroom 2017). This is true for climate change and its impacts in the rural areas. The population is not well informed as to what really is climate change, the causes and the effects. They are only enduring the effects ignorantly. The majority of farmers in the rural areas are subsistence farmers and their seasons are governed by the four seasons namely Summer (November, December, January and February), Autumn (March, April and May), Winter (June and July) and Spring (August and September).

The FAO have come up with a term they coined e-agriculture. E-agriculture refers to the use of ICTs in designing, developing and applying innovative ways to improve agricultural production. According to FAO-ITU (2017) e-agriculture offers strong potential for driving economic growth and rising incomes among the rural folk through increased efficiency of agricultural production, improved livelihoods and value chain development. It can also play an important role in addressing some of agriculture’s most pressing challenges, which include climate change, loss of biodiversity, drought, desertification, promoting agricultural trade, high individual risk and inefficient supply chains. It is important to note that ICTs also offer to transmit information about climate change, new methods of farming and tools to use new, seed varieties that suit climate change, other inputs and information about new markets and market prices at a relatively low cost, hence having a significant contribution to agricultural growth. This makes farmers learn from information disseminated via ICT devices/tools.

Many developed countries have adopted ICTs and implemented it in their agricultural processes. USAID’s Famine Early Warning System Network has been providing early warning and analysis on acute food insecurity. This includes monthly reports and maps detailing current and project food insecurity, timely alerts on likely crisis and specialised reports on weather and climate, markets and trade, agricultural production, livelihoods, nutrition and food assistance are disseminated to the relevant authorities through the system. As a result of the use of this system, the authorities are in a better position to plan and influence certain agricultural decisions in a proactive manner to try and avert the forecasted disasters.

Smart Agriculture

The agricultural sector has witnessed drastic changes, shifting from traditional farming methods to a more informed approach which has been termed precision agriculture. Precision agriculture is a farming management concept based on observing, measuring and responding to inter and intra-field crop variability (Zhang & Kovacs, 2012). This has been greatly facilitated by the ability to collect as much data as we can with ICTs. The advancements in technology has led to our ability to process data and analyse the most intricate attributes of that data, giving us the leeway to make informed decisions. Various technologies can be combined to achieve this once formidable task. At its inception, precision agriculture was primarily focused on spatial variability within agricultural fields, recognizing that traditional, uniform management of these fields was neither efficient nor sustainable (Bongiovanni & Lowenberg-DeBoer, 2004). In the 1980s, GPS and GIS was gaining popularity in the United States. The launch of the satellites opened up a new spectrum of data which could be collected and manipulated. Half a century down the line, technologies such as Internet of Things (IoT), Big

Data etc. are now easily accessible to communities. The combination of these technologies has resulted in autonomous combine harvesters,

Climate-smart agriculture (CSA), a concept developed by FAO, is an approach to developing the technical, policy and investment conditions to achieve sustainable agricultural development for food security under climate change (FAO, 2013). It is not a prescribed practice or a specific technology that can be universally applied. This is to say each country or region researches and develops policies and technologies which suit them best to achieve the three main pillars of climate-smart agriculture:

- Sustainably increasing agricultural productivity and incomes;
- Adapting and building resilience to climate change;
- Reducing and/or removing greenhouse gases emissions.

In simple terms, any farming practise developed to reduce CO emissions, as well as preserve the integrity of the soil whilst maximising productivity is climate smart agriculture.

RESEARCH METHODOLOGY

A quantitative and qualitative research designs were carried out to inform the data collection and analysis process in this research. However, the research is largely quantitative. The data collection technique was in the form of questionnaires augmented by interviews. These questionnaires were handed to the respondents (n=157) to fill. The respondents were rural farmers selected from Tsholotsho District in Matabeleland North Province in Zimbabwe. Firstly, the demographic questions presented and meant to define and elicit the non-confidential profiles of the rural farmers as shown in Table 1. Subsequently, the research questions followed to enable the assessment of adoption and utilisation of ICTs in rural agriculture as shown in Table 2. The response rate was 100% and all questions were answered correctly as instructed. The data collected from the respondents was then analysed using SPSS and the findings were presented in Tables and Figures. The results derived from the analysis are discussed in the subsequent section.

Table 1: Farmer Profiling Questions

Demographic Questions
what is your Gender?
What is your age?
What is your level of education?
Do you own any ICT device?
Are you connected to the Internet?
What is the ICT communication platform you are using?
What activities are you doing for a living?
Have you ever accessed agricultural information using your device?
Where do you sell excess produce?

Table 2: Research Questions

What is the current state of ICT adoption in Zimbabwean rural agricultural development?
What are the potential benefits of ICTs in Zimbabwean rural agricultural development?
What are the challenges hindering the successful implementation of ICTs in Zimbabwean rural agricultural development?
Are the rural farmers informed about issues of climate change and their effects?

An overview of the research problem and objectives are given. It then presents the research questions and sampling strategy, data collection methods and data analysis techniques used in the study.

The research problem is; inadequate utilisation and non-affordability of ICTs in rural agricultural development despite the potential benefits. The objective of the study is to investigate the role of ICTs in rural agricultural development and identify the factors that hinder the successful adoption, implementation and utilisation of ICTs by farmers in rural agriculture for the purposes of information gathering and dissemination in the wake of climate change.

Sampling Strategy

The study uses stratified random sampling technique to select the study participants. The population of the study were farmers in rural areas of selected community. The study divided the population into homogenous strata groups based on their socio-economic status, gender and age being guided by the principle that the strata should not overlap and that they are made up of the whole population. The study then randomly selected a sample from each stratum.

Data Collection Methods

The study used two data collection methods: questionnaires and interviews. The questionnaires collected quantitative data on the adoption, implementation and utilisation of ICTs in rural agricultural development, dissemination of agricultural information and devices used. The interviews collected qualitative data on the potential benefits of ICTs in rural agricultural development, information dissemination and the challenges faced.

Data Analysis Techniques

The study used descriptive statistics, correlation analysis and regression analysis to analyse the quantitative data collected through the questionnaires. The study used thematic analysis to analyse the qualitative data collected through the interviews.

Data Presentation

Data was entered and analysed using Microsoft Excel as well as Statistical Package for Social Sciences (SPSS). Results were presented using Tables and Figures.

Demography of participants

To fully make sense of the data collected, a background of the respondents in the form of demographic study was necessary. The characteristic include gender, age and level of education.

Table 3: Rural Farmers Demography

	Frequency	**Percent**
Males	71	45.2
Females	86	54.8
Total	157	100.0

The majority of respondents were females who constituted 54.8% of the respondents (Table 1). This is characteristic of most rural agriculture based communities. Most men have migrated to urban areas in pursuit of different career options and better opportunities while women are left at home doing most of the agricultural activities.

Table 4: Farmers' Ages

Age Category	Frequency	Percentage (%)
18-24	32	**20**
25-34	64	**41**
35-50	52	**33**
50+	9	**6**

The age of famers in rural communities range from 18 – 50. However, the most energetic group that normally fends for families in rural areas and own cell phones are in the range 25-34. Agriculture requires very strong group that can work in agriculture throughout the day to make sure production is maximised.

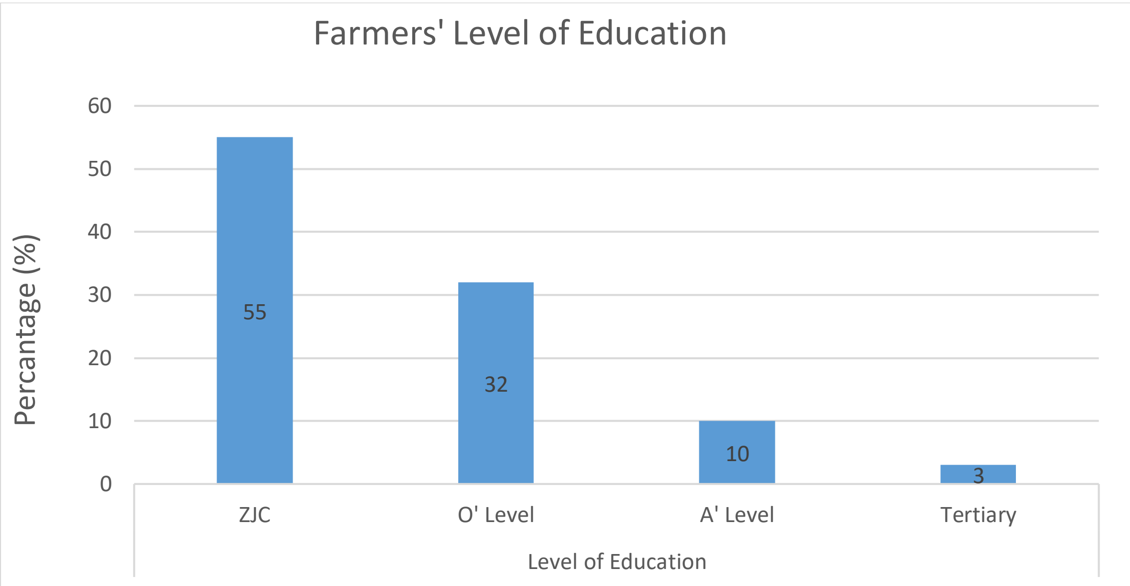

Figure1: Farmers' level of Education

The level of education of farmers in rural areas are mostly primary and secondary education. Zimbabwe Junior Certificate (ZJC) constitute 82%, Ordinary Level (O' Level) 76.4%, Advanced Level (A' Level) 33.7%. Only 0.02% of farmers in rural areas went to tertiary institution and attained certificates. However, this can be attributed to the rural urban migration as those who would have attained such certificates are migrating to the cities and towns.

In this part of the survey, researchers focused on the widespread of ICT and its enabling factors in order to access the potential impact it could make in rural population.

Respondents were asked to tick the internet connectivity they have access to, either because of the telecommunication infrastructure available to them or the capabilities of the devices they own. 2G is the most basic and widespread connectivity mode accessible over all phones, smart phone or otherwise in rural communities.

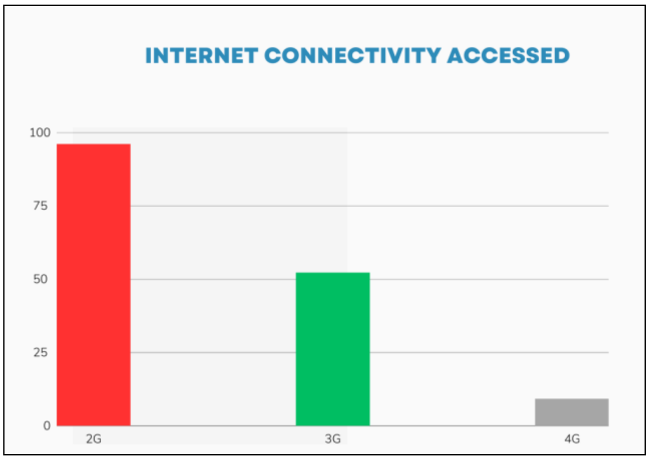

Figure 2: Internet connectivity

The most commonly used form of ICTs communication is short message services, used by all the participants who have mobile phones. However, the most common communication platform they utilise is the WhatsApp messaging platform. This has been helped by the availability of custom data packages for this platform from local internet service providers.

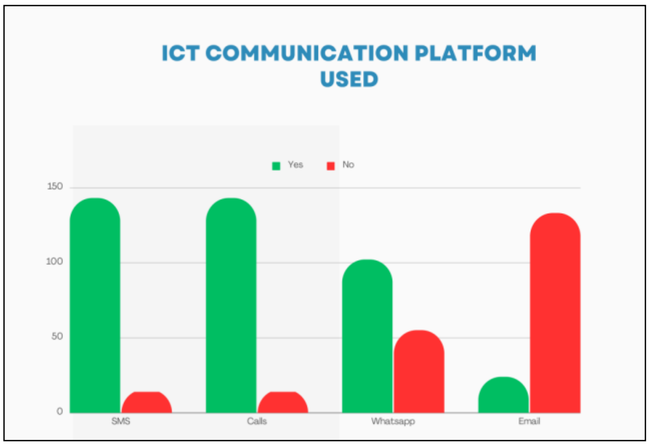

Figure 3: ICT communication Platform used

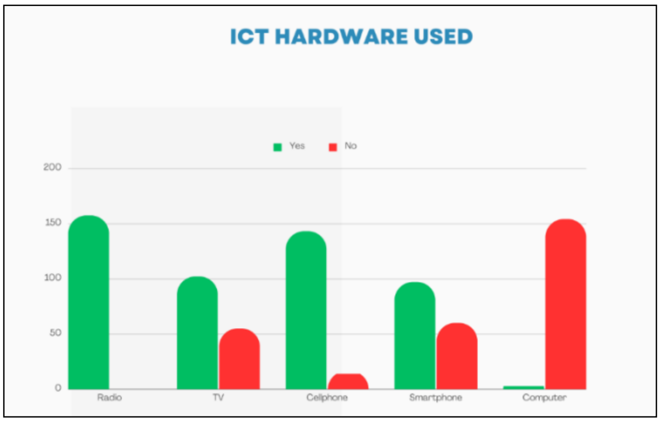

Figure 4: ICT Hardware used

Activities done for a living

The data illustrated in Figure 6 revealed that farming is the dominant activity in the area. However, some people are formally employed, as can be shown by the 10% in the figure below, since they practice seasonal farming. According to Matita et al., (2018), agriculture has remained the main livelihood strategy for many people in low- and middle-income countries (LMICs) as most of them are self-employed.

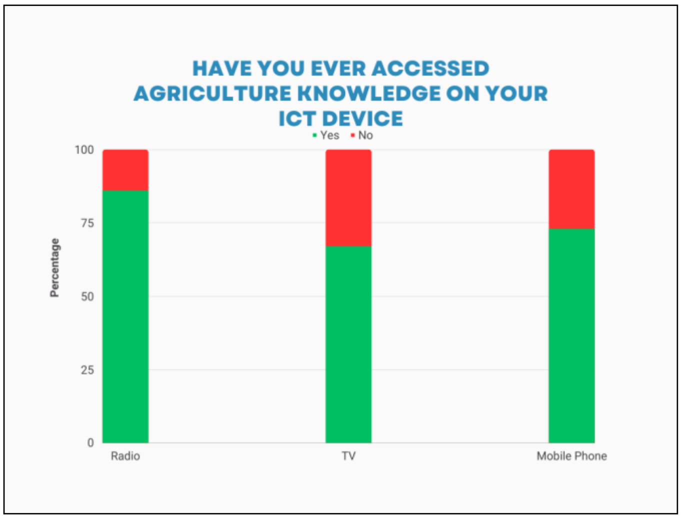

Figure 5: Accessing Agricultural knowledge using phones

The excess produce is sold mostly within the communities, with the Grain Marketing Board being a close second. There's barely any produce which is sold to people from other communities.

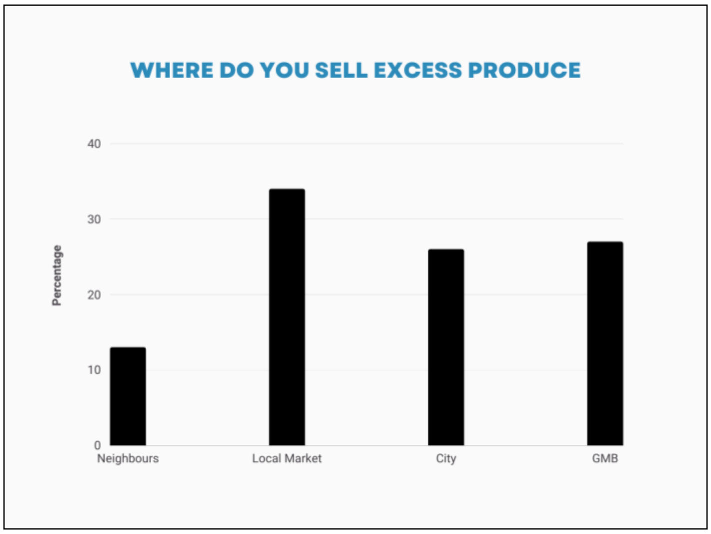

Figure 6: Produce Markets

Rural farmers sell their excess produce to neighbours, growth points, local shops, local schools, bus stops and community centres where community members normally gather for particular activities. This is what constitutes the local market. Some would actually sell at Grain

Marketing Board Depots in their vicinity while others would move their excess produce to cities but it comes with some costs.

RESULTS DISCUSSION

Current state of ICTs in Rural Community

In rural communities, most farmers use 2G, TVs, dump mobile phones, radio and have limited access to Internet. Despite the potential benefits of ICTs, their adoption in Zimbabwe's agricultural sector remains low, particularly in rural areas where the majority of smallholder farmers reside. This is due to several factors, like the digital divide, which is characteristic of most developing countries. The rural farmers are not very much conversant with these ICTs due to financial and skewed knowledge about their adoption and utilisation in agriculture hence low production.

Challenges and Benefits of ICTs in rural agriculture

Research has shown that the adoption of ICTs technologies in rural agriculture has not been without hindrances. Digital divide is the major hindering factor and ICTs' reliance on telecommunication infrastructure. Rural communities face numerous challenges in the adoption and utilisation of ICTs, among them are investment costs, policies, power constraints and lake of awareness.

The history of precision agriculture shows that its evolution started about fifty years ago. However, it is just getting familiar in developing countries such as Zimbabwe. GPS technology might sound as if its new as Zimbabwe recently launched its first briefcase satellite into orbit. It is one of two countries in the entire African continent to send a satellite into orbit. This translate to an incapacity to fully utilise satellite imagery for any purposes because they do not own the data gathering tools required.

Farmers in rural areas need to invest in ICTs and identify their utilisation especially in post-harvest processes, soil management, irrigation, marketing, weather monitoring and forecasting, pest control or even research and development and above all for information dissemination and gathering about climate change and its effects. Data and information on agriculture and climate change effects enable farmers to change behaviour patterns in agricultural activities. Thus these are some of the opportunities that come with ICTs in rural agriculture.

Knowledge about climate in rural community

All the participants acknowledged that they were experiencing climate change. During the administration of questionnaires, the farmers explained how unpredictable changes in the weather patterns have affected their livelihoods and the evidence showing that in deed they are experiencing it. They were however not able to clearly define climate change, but are aware of the changes around them. They also showed that they have little knowledge on its causes as they still practice some of the agricultural practices which are not environmentally friendly and in line with climate change. As portrayed in figure, 25% of the respondents believe that the causes of climate change are both natural and man-made, 30% man-made, 23% natural and 23% spiritual. One's level of education affects one's level of awareness and it also has an effect on how the environment is managed. In this scenario the respondents had a bit of knowledge on climate change and its effects which has aided to their adaptive capacity. However, there is need of more trainings and awareness about climate change to increase their knowledge in order to improve their coping capacity apply other farming methods in line with climate change.

Asked on their understanding of smart agriculture, most farmers have no understanding of what it is. However, the majority have over the past few years adopted new ways of practicing agriculture, the latest example being iNtwasa a scheme that was introduced by Zimbabwe Government in 2017 to boost agricultural production especially in rural areas.

CONCLUSION

As evidence shows, the majority of rural farmers actively practising agriculture in rural Zimbabwe are females. Their male counter parts are migrating to the urban cities in pursuit of better opportunities. Just like any other subject, the more one is knowledgeable in that domain, the better the quality of decisions they are bound to make. Climate change is a reality, with the population interviewed in this study acknowledging the impact it has had on their practices and lives. However, climate smart agriculture approach is obviously attractive and compelling in principle, but its application under Zimbabwe's diverse agro-ecologies and highly heterogeneous farming systems, socio-economic conditions and policies still requires concrete examples of success. The evidence of how such successes are measured and achieved is of critical importance (Neate, 2013).

According to this study, one of the most significant obstacles that stands
in the way of the success of rural farmers is their lack of access to various financing resources. After this comes problems with transit and lack of functionality in the market infrastructure. The findings of the study indicated that there was an inadequate quantity of data in rural agricultural development. Rural farmers need to be knowledgeable about a variety of various aspects of agricultural marketing, such as where they can acquire financing, how to keep their commodities fresh, how to package them and how the market is functioning (Hariharan et al 2023). Governments had to establish transparent criteria for the sale of agricultural products in order to shield farmers from being taken advantage of or suffering financial losses. In other countries, there is typically a system of crop insurance in place to ensure that farmers make at least some money off of their harvests. Infrastructure, which includes roads, ICT communication networks and electricity sources, particularly in rural areas, requires significant financial investment from governments in order to be upgraded and expanded rural farming.
Gleaning clear empirical messages to inform farmers and policy makers and support any scaling up initiatives will depend on how the climate smart agriculture concept is understood in practices, allowing for adaptations and continuous two-way feedback mechanisms between researchers and practitioners, farmers and policy makers. Farmers often have difficulty accessing markets because of inadequate infrastructure for information gathering and dissemination, low productivity levels, inconsistences in supply and low quality due to poor post-harvest practices.

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PLANNING OF PASTORAL ROUTES AND DYNAMIC SETTLEMENTS FOR ADAPTATION AND OPTIMIZATION OF USING COMMON RESOURCES

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ABSTRACT

There are two main economic activities for the majority of Darfur's population and other parts of Sudan: farming and herding. Open livestock corridors and routes for traditional pastoralism are some solutions suggested to avoid the problems arising between farmers and routing pastoralists over natural resources. It's one mechanism to govern the land uses that were historically divided between tribes or mutually utilized in different modes of land use. Transhumance is a system to adapt to the environment which will make it impossible to change their lifestyle. This research project suggests planning the trajectory of pastoralists' routes, adopting their needs during the settlements and grazing with an optimum governance framework (OGF), and supporting mutual livelihood. We will employ qualitative analysis and use technology to find the proper track, capacity of the land, and access to resources to mitigate the possible clashes between pastoralists and farmers. To achieve these goals, we propose using monitoring and mapping systems that include technology such as LoRaWAN, field global position system (GPS), remote sensing, and geographic information system (GIS). The insight results from the system are used to induce a common resources governance policy framework. This system aims to contribute to planning space and resources for the forgotten population in urban planning discourse and promoting sustainable peace and security for the two livelihood groups that are considered the backbone of the economy of Sudan. Additionally, recording the access of herds to farms and violence and comparing them with cultivating activity and other factors can help to build patterns for land-use and land-cover change and help for future common resources governance strategies.

Keywords: *planning, pastoralists routes, dynamic settlements, farmers, land-use, common resources, optimum governance framework, mapping, technology*.

Introduction

Farming and herding are the primary economic activities for most of the population in Darfur and other parts of Sudan. Developing and establishing livestock corridors and routes for traditional pastoralism can help prevent conflicts over natural resources, which often arise between farmers and roaming pastoralists. Transhumance, a system where pastoralists migrate seasonally with their livestock, is an adaptive strategy for the environment.

A demarcated route is a road dedicated to mobile livestock with a width of 150 m demarcated with fixed-colored cement markers. They are 1-3 meters high and located on both sides of the routes at intervals of 1-3 km. Where red indicates pastoralists are close to cultivation, yellow warns that the cultivation is not near but reachable by animals, and white indicates the safe distance of cultivation (Youssouf 2008).

The reasons for the conflict in Darfur can be identified from social, economic, cultural, and political perspectives. In this paper, we focus on the environmental dimension. The herders and farmers in Darfur compete over diminishing natural resources. Among other factors, climate change, drought, and water scarcity caused rising tension and became a source of instability in Darfur.

This paper proposes an approach for planning and developing the trajectories of pastoralists' routes, considering their needs during settlement and grazing, while seeking an optimal governance framework that supports mutual livelihoods. We will employ qualitative analysis, along with remote sensing and Internet of Things (IoT) technology, to devise governance strategies, determine the appropriate land capacity, and ensure access to resources to mitigate potential conflicts between mobile pastoralists and farmers. Our proposal includes using monitoring and mapping systems that incorporate technologies such as remote sensing, Geographic Information Systems (GIS), solar-powered devices, and IoT. By recording and tracking the movement of herds, and incidents of violence, and comparing these with farming activities and other factors, we can identify patterns of land use and land cover change, which will inform the development of future common resource governance strategies and policy frameworks. Collecting, analyzing, and making this data available to beneficiaries will be crucial in achieving these goals.

Previous and current condition of corridors and routes

In Darfur, for more than 4 decades, the common resource along the way of the herds' mobile was the source of conflict with farmers. Despite many trials to build peace, it did not last for the long term. This section presents how mobile pastoralists adapted traditional practice through corridors and routes in various circumstances.

Sulieman and Ahmed studied changes in eastern Sudan's land use and cover from 1979 to 2009. They used remote sensing to find that the natural vegetation decreased from 26.9% (1979) to 12.6% (1999) and declined to 9.4% (2007). Mainly, the natural cover was reduced in favor of agriculture. The decline in rainfall was another factor. Illiteracy is a factor that caused the pastoralists not to participate in decision-making regarding land use (Sulieman, 2013).

Suleman and Young published a significant study about pastoralists' livelihoods and routes. They said that the pastoralists in Darfur face tremendous challenges. The reason behind the mobility of pastoralists is to enable the herds' access to good-quality pastures during the rainy season and avoid the herds' unsuitable conditions such as mud, flies, overcrowding, and grazing. They used GPS to track 13 livestock keepers to identify their routes and corridors. However, they classified three types of routes: home area, close grazing, and long-distance grazing land. They concluded that mobility is governed by two main factors: security conditions and water (Sulieman and Young, 2019).

The indigenous knowledge of pastoralism is reflected in the wise use of land. For instance, Kababish pastoralists have two different pathways in their annual journey to not overgraze their lands (Helen Young, 2013); (Asad, 1976); (Sulieman and Young, 2019).

The distribution of pastoralist groups in Darfur has not remarkably changed since the Sultanate. The Abbala (camel herders) were in the northern semi-arid areas, and the Baggara (cattle herders) were in the southern belt, and the farmers sandwiched them. In Darfur, the colonial administration demarcated 11 herd routes for 5000 km in length. The routes are wider in the northern areas, where there is poor agricultural land, and gradually narrower in the southern fertilized areas (Babekir and Izzy, 2008).

The mutual interests of the two groups are that historically, the herders fertilized the soil, transported the harvested crops to markets, and sold meat and milk to farmers. Meanwhile, the farmers let the herds graze on their farms after harvesting and offered flour and grains to pastoralists (OCHA et al., 2005).

Pastoralism is a way of life that serves as an adaptation to the environment. Through this lifestyle, herders have developed a deep understanding of their ecosystem and gained local knowledge to improve their herding practices. For example, they demonstrate resilience to security challenges by adjusting the distances of their routes.

The change of the pastoralist routes pattern

During the 1980s, drought waves hit Sudan, profoundly affecting farmers and pastoralists. It resulted in poor pasture in the north, and the nomads' pastors had to move to farmland. The farming rangelands were expanded and commercialized. Also, the relatively wetland in the south was taken over by wealthy farmers and pastoralists. The traditional livestock routes were blocked by the expansion of new investors in herds and farming. In addition, the farmers started selling the crop's residue instead of letting the herds graze as in the past (Young et al., 2005). Babiker and Izzy explained the factors why the routes became a source of conflict: Increase in the number of mobile animals accompanied by groups of people to guard the herds; dysfunctionality of administration; not enough demarcations on routes; expansion of mechanized agriculture; blockade of water sources on the routes and burning of the grass in the pasture; grazeland is used for producing fodder.

the pastoralists to change their usual mobility to shorter distances, as explained in Table 1.

Table 1: The change of pastoralists' traditional livestock routes in Darfur [source: Young et al 2005, p.131]

Season	**Month**	**The area on the migratory route. pre-crisis**	**During the crisis**
Winter - dry season	January February March	Wadi Azoum - El Tiraig Wadi Salih Kibar	Area inaccessible
Summer - hot season	April May June	Um Dukhan Wadi Salih - Altiraig Wadi Azoum – Saga	Wadi Azoum Wadi Azoum/Saga, in an area called Gaili, which used to be a transit point. In 2003 herders had to stay at this point throughout June and July.
Autumn - rainy season	July August Sep/Oct.	Kabakbiya - Baray Abusnout - Al Dor Al Wakhaim - Al Gisou	Saga Kabkabiya - Um Bari Jidar and Kabkabiya
Winter - dry season	November December	Kabkabiya area Um Bari – Saga	Area inaccessible

Due to limited natural resources and the repeated clashes between mobile pastoralists and settled farmers in Darfur (Pantuliano 2007a), the mobility pattern has changed. The camel herders did not head to the normal southern fringes of the northern deserts, and cattle herders did not move to traditional grasslands as before (Young et al., 2005). The conflict in Darfur forced .

Obviously, from the table, the pastoralists changed their routine corridors, routes, and settlements to adapt to the difficulties and changeability of security and water. In the interview with practitioners, they said that before they crossed paths with their herds on a tribe land (hakora/Dar), there was an agreement between traditional leaders.

The British colonial government initially established the mobile herd routes and corridors in Darfur. Over the years, the region has undergone significant changes, including the effects of climate change, population growth, security issues, changes in vegetation cover, and drought. Additionally, various political, social, economic, and cultural factors have influenced these routes. As a result, herders have been compelled to seek new routes to ensure the survival of their livestock.

The management of common resources

There are two dominant economic activities in Darfur: herding and farming. Both groups completely depend on natural or common resources. The way they manage its utility and the role of the government are discussed in the following section.

The problem of the management of land use has been rooted since 1944, during the British colony of Sudan, where the "Soil Conservation Committee's Report" stated that in the conflict of interest that took place between settled inhabitants and nomads, priority should be given to the settled (Sudan Government 1944, 15). Since the 1960s, the spreading of planned and unplanned fed-rain agricultural lands has caused the shrinkage of grazing land in the savanna belt (Shazali and Ahmed 1999). Regarding the challenges of expanding agricultural schemes, the pastoralists were forced to adapt accordingly (M. Ahmed, 2014).

Babiker and Izzy, in their work, mentioned many factors affecting livestock mobility in Sudan. Since the colonial period, successive governments have stated policies biased towards modern agriculture. Additionally, throughout the history of modern Sudan, the legislation governing land and natural resources gave the inhabitants of the land an advantage. They noted that pastoral mobility legislation needed to receive adequate attention at either the federal or state level. The writers said there is no overall map of pastoral corridors for the country. In 1996, there were endeavors to discuss the route map in parliament, but the dispute between the Ministry of Agriculture and Animal Resources over authorities delayed it. However, four states (North Kordofan, South Kordofan, North Darfur, South Darfur, Gadarif, and Sinnar) passed legislation to regulate livestock mobility. Another factor is that in 1970, the government canceled the native administrations that cooperated to manage the natural resources among farmers and herders, depending on indigenous wisdom. Reconstruction of the local authority system without an appropriate level of legislation caused a weak contribution to taking action against a probable conflict (Babekir and Izzy, 2008).

There were some initiatives established to mitigate the conflicts between farmers and pastoralists and different pastoralist groups. In 2005, the president issued a presidential decree to establish a committee for protecting and developing pastoral mobility and routes. The committee involves authorities with concerns and stakeholders, including farmers and pastoral unions. The committee, in cooperation with the Sudanese Pastoralism Society (SPA) and a local non-governmental organization (NGO), carried out some achievements in South Darfur State, as shown in Table 2.

Table 2: Delineation of routes in South Darfur: [Source: Sudanese Pastoralism Society 2007]

Route Name	**Km**	**Interventions**	**Year**
Totah	220	- Provision of water and rehabilitation of 9 water points (WP). - Range rehabilitation: water spreading, fodder planting (at 3 sites) and range reseeding. - Education: establishment of 6 primary schools. - Veterinary services at 2 sites.	2005
Domaya- Dar Fallata	245	- Provision of water and rehabilitation of 8 WP. - Range rehabilitation and protection: fodder planting (2 sites), range reseeding (9 sites). - Education: establishment of 6 primary schools. - Veterinary services: establishment of two mobile hospitals and 2 animal breeding centers. - Establishment of police points in two areas.	
Wadi Hawar Dar Taaisha	420	- Provision of water: drilling of 6 surface wells, 3 deep wells, and 3 hand pumps. Excavation of 6 hafirs. - Range rehabilitation: range reseeding around Sawani, and organization of range extension programmes. - Education: establishment of 8 schools. - Veterinary services: establishment of 4 mobile hospitals and training programmes. - Establishment of police points at two sites.	2005
Samaha	132	interventions not listed	2005
Dar Alsalam (Eastern route)	57	ọ	2005
Bigera Shailah	250	ố	2006
Buram route being demarcated	250	ố	2007
Total	**1574**		
Dehail Dabi			2008
Slaim-Wadaa			2008

“The Tragedy of Common” explains that the individual herdsman can misuse and overgraze the shared pastures over the group's interests (Anukwonke, Charles, 2015). Therefore, increased animal numbers reduce food production and cause soil depletion (Anukwonke, Charles, 2015). Garret Hard introduced the term “tragedy of common" in 1968 and suggested avoiding this problem by privatizing the lands. Afterwards, Elinor Ostrom, a Nobel Prize winner, documented through her works that the local communities have developed their knowledge and wisdom to manage the common pastures sustainably without privatizing them. Also, she highlighted that the solutions developed by local communities would not be maintained if the land were taken from them. In the same published article, the writer proposed a group of solutions for the common tragedy. Governmental intervention can mitigate the collective action problems. Authority regulations can control extended individual interests. Issuing rules by the government to limit pollution. Privatization of public property lands is also a suggested solution. (Anukwonke, Charles, 2015).

Many factors affected the routine of mobile pastoralists' resource management practices, in particular in Kordofan (Babiker, 2008). It includes the prolonged dry period that forced the pastoralists to move close to the farms. Negative human impacts on the environment include developing the oil industry and its infrastructure, the construction of pipelines obstructing access to water points, and deforestation (Siddig et al., 2007). Significant increase in the mechanized farms in the clay plains. Increase in the population and animal numbers (UNDP, 2008). Change the traditional routes due to insecurity. Some practices of settled communities, for instance, burn crop residues to prevent animals from grazing. Producers of gum Arabic prevent the animals from feeding in acacia forests (Siddig et al., 2007). All the mentioned factors have played a role in increasing the tension between farmers and mobile pastoralists.

Table (3) List of conflict analyzed in 20 case studies in Kordofan [source: IFPRI 2006 p.71]

	Conflict type	**Number of cases studied**
I	**The conflict between pastoralists and farmers**	**10**
	Overland and pasture around stock routes and in village land.	7
	Overuse of hafirs	2
	Around plots cultivated as vegetable gardens.	1
II	**Conflicts between “new settlers” and “Dar” holding tribes**	**4**
III	**The conflict between pastoralists/farmers and large private investors and the state**	**5**
	Over-mechanized agricultural schemes	2
	Over-areas covered by oil investments	2
	Over-areas covered by other private investments.	1
IV	**The conflict between upstream and downstream water users**	**1**
	Total	**20**

The figure in Table 3 shows that the conflicts rose, mainly, over common resources; water and land. Confronting authority came second.

Previous studies of technology have been used for common resource planning

In this section, we will discuss attempts to utilize technology in addressing environmental issues. Technology plays a crucial role in providing information, connectivity, and monitoring, which enables quick intervention. In Uganda, historic poaching records and geospatial park data have been used to design the Protection Assistant for Wildlife Security (PAWS). This system can predict and identify potential poaching locations, helping patrol routes to be more effective in providing protection (Kendra, 2017).

To prevent the corruption that facilitates deforestation and illegal logging, the World Resources Institute and Moabi launched the Logging Roads Initiative to collect data by tracking and recording logging roads in the Congo Basin rainforest. This project is an open-data portal hosting 13 years of satellite imagery from various companies. It contains layers of oil and mining concessions, agriculture, and logging. The task manager and the main tool for drawing logging roads are OpenStreetMap (OSM). It is a platform where volunteers collaborate for online mapping based on satellite imagery. This project aims to improve the awareness of the community regarding natural resources by sharing the progress of the project and information about the situation of logging in the Congo basin (Kenda, 2017).

Cisco and Dimension Data launched a real-time data collection project called “Connected Conservation." The innovative initiative is designed to reduce poaching on South Africa's wildlife reservations. It is monitoring the mobility of people rather than animals. In 2016, only one rhino was hunted, and in 2018, no rhino was killed (Singapore Global Centre, 2020).

Bauer and Magri used a GIS geographic information system to investigate environmental features in Prorong at the Central Tibit to structure a pattern of resources used by pastoralists. The authors utilized livestock corrals as georeference locations to determine grazing areas. Also, they benefit from the normalized difference vegetation index (NDVI) values to assess inter- and intra-annual pasture productivity (Bauer, 2010).

Recently, technology has been effectively utilized for environmental applications, particularly in Africa. As seen in previous work, it is used to monitor large areas of natural reserves and plays an important role in providing valuable information.

Technology for corridors, routes, and dynamic settlement in Darfur

Planning the trajectory of pastoral routes and dynamic settlements is crucial for mitigating conflicts between mobile herders and farmers. This can be achieved by adapting and optimizing the use of common resources. The process begins with collecting data on the ecosystem, including corridors, routes, and services in the temporary settlements of herders. The collected data is then analyzed and shared with the community, government, civil society organizations, media, and other partners. This information is essential for developing strategies and issuing regulations, rules, laws, and codes that govern the relationship between farmers and herders and the use of common resources. Using updated information to plan routes and corridors, rather than relying on paths established nearly a century ago, can also better address current needs. Additionally, the local knowledge accumulated over years of practice should be regarded as a key reference.

Technology is an important tool to realize this vision. The pastoralists and farmers represented in associations should act as main players and active participants. It is necessary to train a joint committee of pastoralists and farmers to be a source of information. Also, they should participate actively in planning and issuing regulations and laws. They will send information to the shared online platform. The information portal will help in defining the optimum governance framework for planning and managing common natural resources.

Additionally, it will contribute to the provisioning of water points, veterinary services, and other essential needs for beneficiaries. In addition, continuing to upload information creates a database that can be used by OGF to manage common resources and device strategies for the future. Besides, the information can help measure the effects of climate change, the annual rain rate, the pasture situation, the expansion of agriculture in routes and corridors, the location of herds, and the condition of livestock. Information platforms can play a significant role in identifying the areas that witness repeated tension between farmers and pastoralists to determine the reasons and solve the problems instantly.

As mentioned in previous studies, the researchers implemented various technologies for environmental applications such as GIS, GPS, and remote sensing. The technology is developing quickly, and many advantages have been integrated into one device. Here, we propose to use LoRaWAN. It has many characteristics that make it an appropriate candidate to achieve the goal of the paper. It has low power consumption, and its battery lasts for 10 years. The transmitting and receiving signals are over a distance of over 10 kilometers. Without the use of GPS, a LoRaWAN network can use triangulation to locate end devices. LorRaWWAN characterized low-cost end nodes and open-source software (LoRaWAN, n.d.).

The trained members of herders and farmers can use offline tool surveys such as KOBO to collect data. After analysis of the data by experts and specialists, the information will be disseminated on the open platform. The sensor network will be set to measure environmental parameters that might affect the mobility of the herds and the routes and corridors, such as rain rate, position of the herds, and normalized difference vegetation index (NDVI). NDVI is a remote sensing method to detect the healthy condition of biomass in a specific area. The detection of green plants depends on the reflectance of visible light and the near-infrared spectrum. The green leaves display less reflection in the near-infrared wavelength band compared to yellowish plants. (Abdusamea, 2018).

The technical process of LoRaWAN includes the sensor networks connected to the remote terminal unit (RTU) that sends the measured quantities by sensors into the gateway. Then the acquired data are transmitted to cellular network stations. The data are received in the cloud or a specific service provider (LoRaWAN, n.d.).

The planning for the development and governance of resources is important. Resources must be evaluated to determine whether their capacity can meet the increasing demands without overgrazing, farming, or depletion; whether the access pattern raises the tension between mutual benefit groups; and how to develop the resources to meet the requirements of both humans and animals in the dimensions of food, water, and health. To devise a governance framework, a piece of accurate information is a must. This information is needed to correctly assess the capacity of rangeland to the herd without overgrazing, the routes of animals and its capacity to meet the needs without tension arising, and what extends the herder's adherence to routes, the capacity of farms to feed the inhabitants in the surrounding area of the *massar* or route, the access to public services of water, veterinary care, health, and education, the changing of and cover, and early warning of environmental hazards and disasters.

We will utilize three technologies to collect this information to establish an efficient and effective governance framework.

1. LoRaWAN is a low-power sensor network that can easily cover large areas of land and is very suitable for tracking cattle and camels, sensing water resources, and enabling a grid of metrology station measurements to be plotted in fine grain. LoRaWAN uses a sensor unit, the RTU, which is responsible for collecting measurements. It is mainly an affordable solution with reusable ear tags that collect GPS tracks, in addition to a data logger from the Metrology Station. The RTU forwards data to the gateways and then to the network.
2. A grid of metrology stations is used to have accurate weather measurements to estimate and forecast rain and drought. The data logged by this station is forwarded to the central server through the LoRaWAN network.
3. Remote sensing and GIS mapping contribute to the land coverage for all rangeland in the area under study.

These three layers of information will ensure an open dataset for formulating a governance framework, planning routes, and developing resources.

Deploying a LoRaWAN sensor network for monitoring rangelands in Darfur is a feasible and cost-effective solution, especially in the context of conflict. The key benefits include long-range communication, low power consumption, and flexibility in deployment. However, challenges such as security, power supply, and backhaul must be carefully addressed. The use of satellite communication and solar power presents a robust solution for ensuring continuous operation in a low-coverage area like Darfur.

The collected data and shared information on pasture and herd can give an image of the condition of the routes and corridors to help decision-makers and beneficiaries take action to stop any possible tensions and for future planning.

Conclusion

The conflict in Darfur has surged for many inference reasons, ethical, ecological, social, and cultural. This paper focuses on the environmental dimension. We suggest an approach to help mitigate the dispute over common resources between mobile herders and farmers. We proposed to use LoRaWAN as technology to be used by mobile herders and farmers to collect information about the ecosystem of routes, corridors, farms, herds, and other ecological factors. Open platforms where information will be shared will enhance the participation of all stakeholders. The herders and farmers will actively participate in all steps of the information cycle. In addition, employing this technology will be an opportunity to upscale their technical skills as well as enhance their awareness about the impact of climate change. Moreover, the authorities can develop an optimal governance framework for using common resources. This information helps them to plan routes and corridors based on real findings and develop common resources to absorb the increasing demand sustainably. Overall, the deployment of LoRaWAN for rangeland monitoring in Darfur offers a sustainable approach to managing natural resources, despite the challenges posed by the ongoing conflict. The cost savings and operational efficiency provided by LoRaWAN make it an attractive option for such challenging environments, ensuring that critical data on rangeland conditions can be collected and utilized to support pastoral communities in Sudan. The limitation of the suggested approach is that we did not experiment with the design model.

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APPLICATION OF ANALYTICAL TECHNIQUES TO EVALUATE THE MUNICIPAL SOLID WASTE ORGANIC FRACTION IN THE CITY OF TSHWANE

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ABSTRACT

In landfilling, biodegradation of municipal solid waste organic fraction (OFMSW) is a major mechanism that governs environmental pollution such as gaseous and liquid emissions. Application of innovative analytical techniques for waste characterization to identify the physicochemical composition and structural changes of the waste involved during the degradation process leading to emissions is important for sustainable management and treatment strategies for OFMSW. The study reports variations in the physicochemical composition of leachate and their relationship with organic matter stability during the degradation of OFMSW. A conventional (SLR-1) and a hybrid (SLR-2) bioreactor system were utilized for this study. The OFMSW, including wood, paper, cardboard, kitchen, and garden trash, was collected from Tshwane landfill sites in Gauteng. The biological changes of OFMSW were explored through Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and physicochemical parameters.

Progression and dynamics of the degradation processes were reflected by changes in the chemical information relative to the presence of aliphatic (CH), polysaccharidic (C-O-C), aromatic (CH), and phenolic (OH) structures. The decomposition state was established by the presence or absence of distinct bands in the spectra. The pH and COD stabilized around 7.98 and 28 000 mg/L, respectively, but the COD then declined to <500 mg/L for SLR-2 and <10 000 mg/L for SLR-1. Hybrid operations effectively aided biodegradation by 11.79% compared to conventional operations. These results were confirmed by heat flow curves reflecting different phases of degradation, which illustrated the change of enthalpies and revealed the status of the samples' profiles. The acquired results support the concept of a possible relation between the thermal and biological stability of the investigated waste and, therefore, the feasibility of characterizing municipal organic waste stability using thermal analysis. These can also be beneficial in establishing strategies for sustainable management and treatment of OFMSW to reduce its environmental impact.

Keywords: *DSC; FTIR; Leachate; Municipal solid waste; Organic fraction.*

INTRODUCTION

Economic expansion, urban development, population growth, and industrialization rates have all contributed to a significant increase in global waste generation (Kaza *et al*., 2018; Abunama *et al*., 2021; Longfor *et al*., 2023). About 70 % of the generated municipal solid waste (MSW) ends up in landfills or on uncontrolled dumpsites, and in sub-Saharan African countries, approximately 24 % of the MSW is disposed of in landfills, while the rest of the waste is disposed of in open dumps, water bodies, streets and other undesigned areas (Longfor, 2023). Most of this waste is biodegradable organic waste which is estimated to account for an average of 57 % of MSW in the region (Godfrey *et al*., 2019). Inadequate management of this waste degrades public health, depletes natural resources, and pollutes the environment, all of which have an influence on citizens' quality of life and contribute to climate change (Jaimon, 2017).

As a developing country, the Republic of South Africa (RSA) is faced with a challenge of solid waste management (SWM), due to the rise in waste production. According to the Department of Environmental Affairs (DEA) (2018), the country produced 121 million tonnes of waste in 2017, which is an increase from the 108 million tonnes recorded in 2011 (Godfrey *et al*., 2017). This phenomenon is driven by population growth and improved economic conditions, resulting in uncounted waste. About 95 % of all waste produced is landfilled, and 87 % of municipalities nationally lack the infrastructure and capability to adequately manage and implement waste minimization strategies (Nyika *et al*., 2017). In 2018, up to 75 % of generated waste was disposed of in landfills in RSA (Ngalo and Thondhlana, 2023) signifying the heavy reliance of South African waste management on landfilling and open dumping which on the unavailability of landfill gas capture, the landfills generate greenhouse gases (GHGs) which are harmful to the environment. This is concerning since there is a significant shortage of landfill space in the country. Furthermore, SWM lacks coordination and enough funding, putting the nation two to three decades behind wealthy nations like Europe (Godfrey and Oelofse, 2017).

Currently, bioreactor landfilling is the most ecologically applicable ultimate destination of waste (de Medeiros Engelmann *et al*., 2018). Bioreactor technology has been developed to accelerate the biodegradation of MSW in landfills by promoting conditions necessary for microbial growth (Xu *et al*., 2014; Kumari & Raghubanshi, 2023). The degradation process is facilitated by liquid or leachate circulation augmentation strategy used in bioreactor operation, in contrast to conventional landfilling, which limits the interaction between waste and water during operation (Ismail *et al*., 2019). The recirculation of leachate into the waste mass increases the water content of the bioreactor landfill and provides the distribution of nutrients and enzymes between the microbes which enhances waste degradation. This promotes earlier disposal site stability allowing for a shorter life expectancy and reduce greenhouse gas emissions which is a key aspect in improving the sustainability of landfill operations in developing countries (Sandoval-Cobo *et al*., 2022).

However, the waste stability needs to be monitored to evaluate the environmental pollutions such as gaseous (landfill gases) and liquid (leachate) emissions. Leachate quality is regularly monitored by means of physicochemical parameters such as pH, chemical oxygen demand (COD), and organic matter (OM), which are known to provide useful information about the stability of MSW in landfilling. The conversion of raw materials into resistant aliphatic and aromatic structure-rich substrates with a high degree of humification is typically associated with stability (Droussi *et al*., 2009). Based on the use of physicochemical analysis and analytical techniques, the structural transformations can be observed during the biodegradation process. The analytical techniques are user-friendly, cost-effective and eco-friendly without any pretreatment of samples.

This paper provides relevant information on the transformation of OFMSW by conventional and hybrid digestion through evaluation of partial-aeration and leachate recirculation effects on the decomposition phases of OFMSW. The digestion was monitored by physicochemical parameters and analytical techniques including Fourier transformation infrared spectroscopy (FTIR) and differential scanning (DSC) calorimetry. The significance of this work entails in generated leachate utilization for humidification of landfilled waste to enhance waste degradation and stabilization monitored through analytical techniques while reducing waterbodies contamination. The study addresses the prolonged waste stabilization and GHGs generation as solid waste management aligning with the United Nations sustainable development goals such as decreasing waterbodies pollution (SDGs 6 & 14), reducing GHG emissions (SDG 13), and preventing ecosystems destruction (SDG 15).

RELATED STUDIES

The study of the characteristics, mechanism, and trends in landfill emissions have become an essential part of waste management research. To achieve a more realistic view of OFMSW degradation and leaching, such studies have utilized simulated landfill reactors (SLR) (Wang and Pelkonen, 2009; Venkatesh *et al*., 2020; Aromolaran and Sartaj, 2023). Simulated landfilling provides the possibility of directly studying transformations in structural and physicochemical properties of OFMSW during the biodegradation processes. Landfill emissions are also evaluated using this technique in which real landfill conditions are simulated in a relatively short period. The application of conventional methods such as physicochemical parameters and analytical techniques has been used in SLR studies (Ledakowicz & Kaczorek, 2004; Pelkonen *et al*., 2006; Bolyard *et al.,* 2019; Sandoval-Cobo *et al*., 2022).

The FTIR spectroscopy is an effective technique for determining and quantifying the structure of various chemical, inorganic, and biological substances (Grube *et al*., 2006) with two major advantages: (1) the samples under examination are not exposed to any chemical treatment, preventing secondary reactions; and (2) all compounds available in the sample are simultaneously identified, simplifying, and expediting the study. The method is frequently applied in environmental analysis, where it shows that during the biodegradation process, the relative intensities of the bands linked to degradable functions (amine, aliphatic, and polysaccharide) decrease, indicating stabilization. On the other hand, thermal analysis has been applicable in characterizing heterogeneous organic materials as an appropriate technique (Fernandez *et al*., 2012; Soobhany *et al*., 2017) to evaluate the organic fraction's combustibility and verifying the type of reaction (exothermic or endothermic) involved in the oxidation of the materials (Lui *et al*., 2013, Protásio *et al*., 2017).

Droussi *et al*. (2009) studied the degradation and transformation of olive-mill residues during composting while Soobhany *et al* (2017) assessed the stability and maturity of MSW composts and vermicompost using the FTIR and DSC analytical techniques. On both studies, the progress in biodegradation was showed through the conversion of peptides, polysaccharides, and aliphatic structures with an increase in aromatic structures. Additionally, the spectra of humic acids extracted from composted MSW showed an increase in oxidized functionalities such as amide and carboxylic groups with maturation (Som *et al*., 2009). The techniques have proven to be effective in assessing the decomposition stages of OFMSW materials (Monahoara & Si, 2017; Abid *et al*., 2020; Syguła *et al*., 2021;) however getting representative MSW samples is difficult and challenging hence studies on landfill leachate characterization has been conducted from SLR (Gamperling *et al*., 2009; Lenz *et al*., 2016; Bolyard *et al*., 2019).

METHODOLOGY

MSW Feedstock

The municipal solid waste used in the study was obtained from the City of Tshwane, Hatherley landfill site. The waste was screened and partially pulverized before commencing with the experiments and the proportions were adjusted according to the composition of the waste. The waste components comprised of the following categories: kitchen (80 %), yard & wood (15 %), paper & cardboard (5 %) which were considered as the organic fraction of the MSW. The waste was mixed until a homogeneous mixture was achieved, then separated into two parts and 5 L of tap water was added in each mixture before being fed into the reactor columns.

Experimental Design and Operation

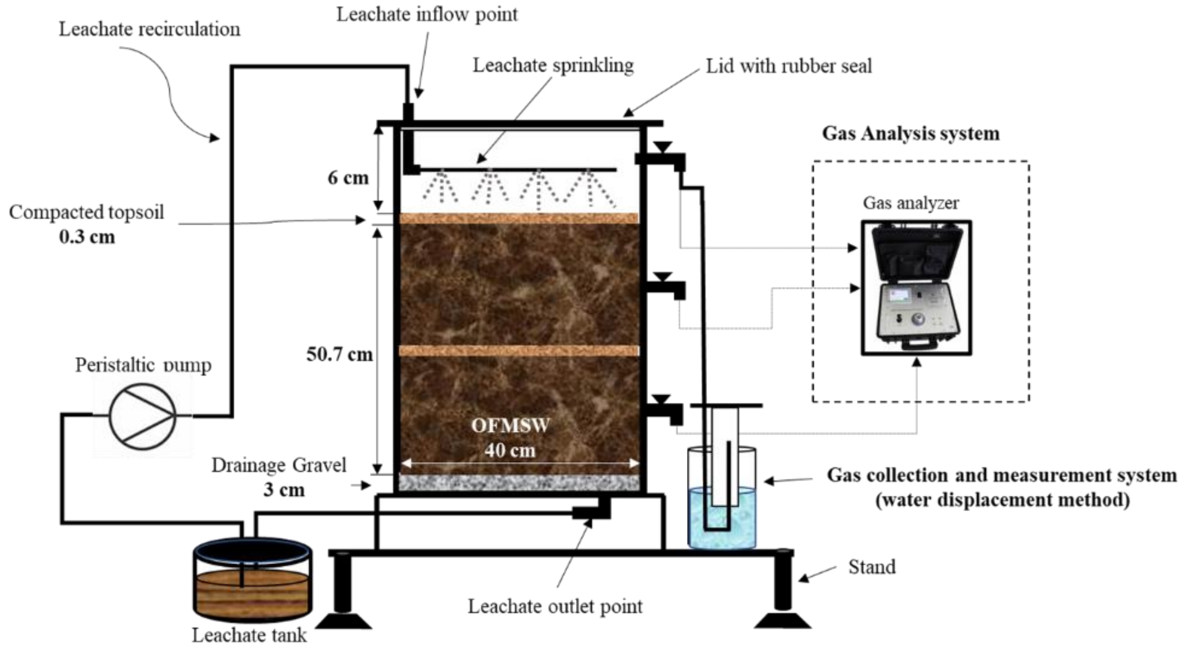

***Figure 1**: A schematic of the simulated landfill bioreactors (SLR).*

The pilot-scale biodegradation experiments were carried out in two (2) simulated landfill bioreactors (SLR-1 and SLR-2). The bioreactor columns were constructed using Plexiglas of 5.0 mm thickness with a holding capacity of 96 L. The effective filling height for the bioreactor columns was 0.51 m. The bioreactors were equipped with gas sampling ports, leachate outlet port at the bottom, leachate reservoir tank, water/leachate addition port on top as shown in Figure 1. The sampling ports are set on the side of the column, lower, middle, and upper, to facilitate even sampling. A leachate discharge port and collection chamber are set up below the SLRs to facilitate the natural outflow of leachate under the action of gravity. A valve is installed to control the leachate outflow. A 30 mm thick gravel layer was placed at the bottom of each reactor as a draining layer preventing blockage of pipelines. Generated leachate flows into the leachate reservoir tank, undergoes pH adjustment using deionized water, and then recirculated back to SLR-2 through a peristatic pump. For conventional operation, SLR-1 was humidified with water while diluted leachate was recirculated on the hybrid operation of SLR-2 at a rate of 1.5 L/day on both operations. Partial-aeration was practiced in SLR-2 operation where the waste was manually turned, on day 29 and 60 after commencing with the experiments.

Analytical Methods

Waste organic matter (OM) content was determined through before and after weight difference method, ASTM D 2974, using a muffle furnace (CF1400 Muffle furnace, MegaDepot) at 550°C for 2 hours, while the pH was measured in the leachate samples immediately after sampling using a multi-parameter bench meter (Starter 3100M, OHAUS). Chemical oxygen demand (COD) was measured using a dichromate oxidation and photometry method in a spectrophotometer (Aqua Lytic, AL800). The FTIR spectroscopy and DSC techniques were used to examine samples of fresh organic waste and leachate at various stages of degradation (4, 6, 10, 15, 20, and 25 weeks). The OFMSW samples were air-dried for 4 days (Hla & Roberts, 2015) at room temperature before being homogenized in a laboratory sample mill (SM-450L, Laboratory-Instruments) and sieved to a particle size passing a 75 µm sieve. Both analytical procedures used powdered, dry materials (12 mg). Leachate samples were filtered, and the filtrate was air-dried before being analysed. An FTIR (Spectrum TWO LiTa, PerkinElmer) spectrometer was used to detect the functional groups contained in the OFMSW and leachate samples. A sample of 12 mg was used to measure the FTIR spectra in the mid-infrared region with a wavenumber range of 4000-500 cm^{-1} at 4 cm^{-1} resolution and 16 scans per spectra. The DSC (PerkinElmer, DSC 6000) technique was used to characterize the OFMSW and stability studies during the degradation process which provided information on the type of transformations occurring during the decomposition of the materials. Nitrogen gas was used at 20.0 ml/min flow rate and heating of materials from 25℃ to 445~~ºC~~ at 5 ℃/min.

RESULTS AND DISCUSSION

Physicochemical analysis

The biodegradation experiments were conducted for 210 days. The monitoring of pH in leachate constitutes is one of the key parameters for determining the stage of waste decomposition. Fourti *et al*. (2011) suggests that an ideal pH for high waste decomposition rate should be within the range of 6 – 8 but once it is outside this range, then microbial activity will be compromised prohibiting or even stopping the decomposition process. The evolution of the pH is shown in Figure 2(a) where the initial values were low ranging between 5 and 6 due to the acidification and hydrolysis process taking place in the waste. Easily degradable ingredients such as polysaccharides are quickly metabolised during early stages of biodegradation which can lead to strong acidification and cause the metabolism to stop (Schnürer & Jarvis, 2018). After 60 days of landfilling, the pH increased substantially reaching 7.5 for SLR-1 and 8.17 for SLR-2, respectively. This change in pH during biodegradation, corresponds to microbial degradation of organic acids especially protein nitrogen (Song *et al*., 2018). The final pH (7.98 for SLR-2 and 6.99 for SLR-1) indicates the formation of humic substances, which acts as pH buffers while the plateau reached after 140 days is an indication of a stabilized organic matter (OM). Organic matter degradation rate during decomposition is significantly used to evaluate the landfill stability and maturity. The OM decreased remarkably over time with mass loses ranging from 39 % at the beginning of the experiments and reaching 25 % for SLR-1 and 19 % for SLR-2, respectively by the end of the experiments.

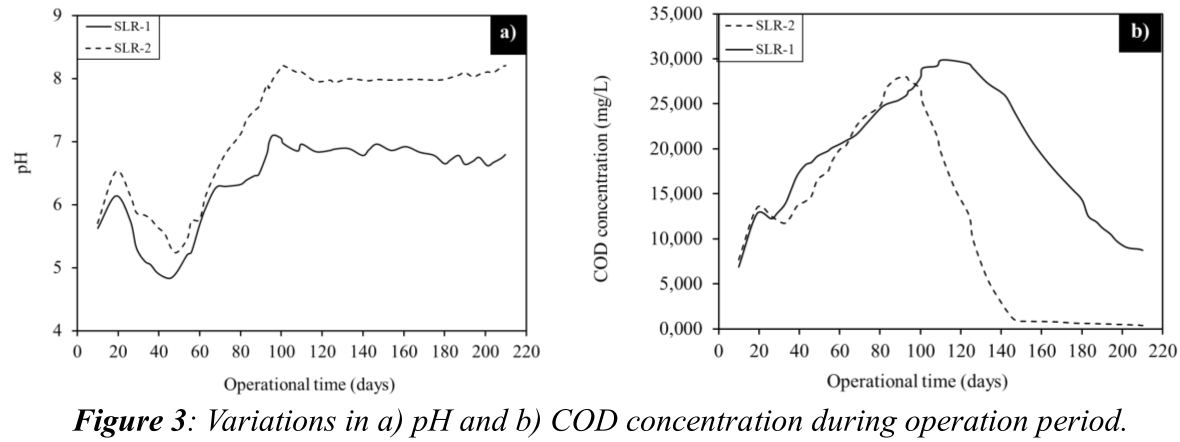

***Figure 3**: Variations in a) pH and b) COD concentration during operation period.*

The COD concentration in the leachate generated from the beginning of the experiments fluctuated greatly from 6 893 mg/L to 21 550 mg/L, as shown in Figure 2(b). After 68 days of landfilling, the leachate COD concentration of each SLR showed a swift increase, with values reaching 29 850 mg/L for SLR-1 and 27 990 mg/L for SLR-2, respectively. This was mostly due to waste degradation and acidification in the presence of oxygen, resulting in amino acids, monosaccharides, and glycerol (Lu & Imlay, 2021; Lui *et al*., 2023) which led to the acidification phase. At the termination of the columns' operation, the COD values declined reaching an average of 8 750 mg/L for SLR-1 while in SLR-2, the COD concentration was below 500 mg/L, respectively. The COD concentration in SLR-2 was much lower than that of SLR-1 due to the conditioning impacts of the leachate recirculation and partial-aeration, which stimulated the generation of hydrolytic enzymes and provided a suitable environment for microbial development, thereby accelerating the removal efficiency of COD from the landfill into the leachate. According to Liu *et al*., (2023), leachate recirculation in landfilling increases humidification and redistribution of nutrients and microbes back into the waste piles, promoting a sustainable growth environment for microbial degradation of organic matter.

Fourier transform infrared spectroscopy (FTIR)

The FTIR spectra of the leachate were evaluated at intervals of 4, 6, 10, 15, 20 and 25 weeks in order to observe the transformation of the organic functions. The obtained spectra were compared to the fresh waste (W0) spectra and were interpreted with reference to spectra assignments of Ouatmane *et al*., (2000), Smidt *et al*., (2002) and Grube *et al*., (2006). The FTIR spectra of samples from SRL-1 and SRL-2 are reported in Figure 3, respectively while the assignment of the infrared adsorption bands is reported in Table 1. The spectra from the two reactor columns exhibited almost similar infrared spectra.

The main adsorption bands to all the samples occurred at 3289 cm^{-1} assigned to -OH groups and C-H bonds of the type of alcohol, phenol, or carboxyl -OH and the hydrogen vibration of amide N-H functions. A shoulder at 1760 cm^{-1} due to COOH groups and a weak band at 1680 cm^{-1} which is a characteristic of aromatic C=C vibrations, in addition to conjugated carboxyl and ketones. A shoulder around 1510 cm^{-1} due to stretching of C=C in aromatic groups, and N-H and C=N in amides, the peaks at 1460 - 1440 cm^{-1} due to aliphatic C-H structures. A band at 1240 cm^{-1} generally linked to the absorbance of ethers, aromatic esters and to the N-H of amides, and a most intensive broad band that appears at 1030 cm^{-1} due to carbohydrates, aromatic ethers and polysaccharides was also common.

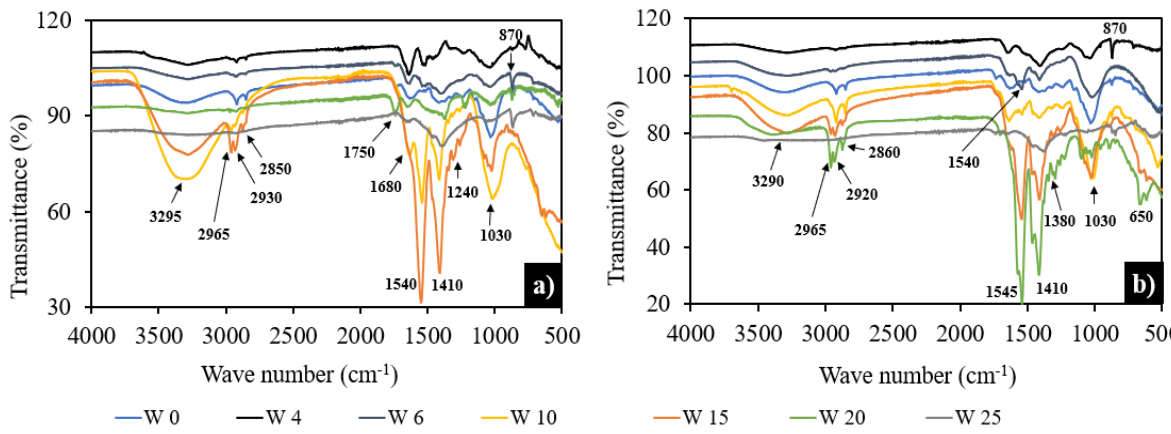

Figure 3: *The FTIR spectra of a) SLR-1 and b) SLR-2, showing stages of biodegradation and stabilization distinguished by spectral characteristics.*

As the degradation proceeded with time, the first significant transformation observed was the appearance of peaks 2920 and 2850 cm^{-1} from W10 to W20 of SLR-2 while in SLR-1, the peaks were observed slightly on W10 and more visible on W15 indicating decrease of the aliphatic fractions in the humic structure and could be attributed to the presence of degraded lipids and carbohydrates in the leachate samples (Li *et al*., 2017; Abid *et al*., 2020). This collaborates with the decrease in carbon content as the OM is degraded. Microbial activity during degradation reduces the intensity of C=O group bands observed at 1680 - 1640 cm^{-1} which finally disappears during W25 on both columns (Abid *et al*., 2020). Another change was observed through the development of a peak around 2965 cm^{-1} on W15 of both reactor columns assigned to C-H stretching in saturated fatty acid chains.

A slight peak was observed around 1740 cm^{-1} in W10 of SLR-2 due to C=O vibration of carboxylic acids, aldehydes, esters, and ketones, signifying an early stage of degradation which appeared in W20 of SLR-1 (Bohm *et al*., 2011). The appearance of 1540 cm^{-1} for SLR-1 (W15) and 1545 cm^{-1} on W10 and its intensity on W20 for SLR-2 is assigned to amide II and could be attributed to a protein origin mostly found in nitrogen-rich decomposed materials. The occurrence of lignin characteristic bands: 1520-1510 cm^{-1} region in SLR-1 (W4 and W15) while 1460 - 1440 cm^{-1} observed in SLR-2 (W15 - W20) was evident for degraded lignocellulosic components (El Ouaqoudi *et al*., 2015). The intensities of bands at 1030 - 1020 cm^{-1} could indicate mineralization from effective biodegradation which may result in an increase in inorganic compounds and typically attributed to the decomposition of carbohydrates or polysaccharides on both columns.

Table 1: *Interpretation of the FTIR transmittance bands and assignment observed during the degradation process of OFMSW in SLR-1 and SLR-2 bioreactors.*

Wavenumber (cm^{-1})	Assignment	Functional group or component
3400 - 3200	O-H stretching, N-H stretching	Hydroxyl groups and amide A in proteins
2970 - 2965	C-H stretching of CH_3	aliphatic methylene
2930 - 2920	C-H stretching of CH_2	Fatty acids & aliphatic methylene
2860 - 2830	C-H stretching of CH_2	Fatty acids & alkanes
1750	C=O	Aldehyde, ketone, carboxylic acids, & esters
1680 - 1675	C=O stretching	Secondary and tertiary amide
1635 - 1630	C=C stretching, C=O	Aromatics and amide I
1545 - 1540	CH_2, CH_3, C-O, & N-H stretching in plane	Amine
1415 - 1410	C-H asymmetric deformation	Carbohydrates and lignin
1390 - 1380	N-O stretching	Nitrate in solid waste samples
1375 - 1370	C-H of CH_2 & CH_3	Cellulosic band
1320 - 1315	C-N stretching	Aromatic amines
1250 - 900	C-O-C, C-O, C-O-P	Polysaccharides and phosphodiesters
1240 - 1230	C-O, C-N stretching	Carboxylic acids and amide III
1030 - 1020	C-O & Si-O stretching, Si-O-Si	Polysaccharides, clay minerals, silica
950 - 940	C-H bending	Aromatic
890 - 870	C-O out of plane	Carbonate and polysaccharides
650 - 630	S-O bends	Inorganic sulfates

The assignments of bands are based on the literature (Ouatmane *et al*., 2000; Smidt *et al*., 2002; Grube *et al*., 2006).

The characteristic band of nitrate observed in 1380 - 1391 cm^{-1} region was an obvious difference in the spectra of leachate samples from W20 – W25 of degradation in SLR-2 and W25 in SLR-1 (Figure 3). The band is usually detected exclusively at a later stage of degradation when the material is well degraded indicating the state of decomposition at which nitrogen from degraded components is oxidised (Grube *et al*., 2006; Fernandez *et al*., 2012; Yu *et al*., 2019). The band position is stable and greatly reproducible at 1384 cm^{-1}. The nitrate band appeared at W15 of SLR-2 and increased with the degradation time until it became a broad band in W25. A high content of nitrogen in humic fractions could be an indicator of microbial enrichment according to Koivula and Hanninen (2001). As microbes die during the degradation process, their nitrogen becomes accessible to the living organisms, and microbial use of cellulose may intensify with time (Grube *et al*., 2006). A weak occurrence of an aromatic amines band at 1320 cm-1 in SLR-1 (W15) which indicates immaturity (Smidt & Meissl, 2007) was slightly observed in W20 – W25, this was because it decreases during biodegradation, and it disappears when the material has reached stability. The occurrence of a weak band at 1240 cm^{-1} assigned to carboxylic acids and amides decreased to a weak shoulder during the degradation process at W20 of SLR-2. Traces of polysulfide and alkyl halides were responsible for the smaller peaks between 870 and 500 cm^{-1} (Soobhany *et al*., 2017)

Differential scanning calorimetry (DSC)

The thermal behaviour with respect to temperature reflects the material's physical properties. Thermal characteristics of waste include the physical properties of all compounds present in the mixture, providing detailed information about its chemical composition. As organic matter decomposes, the material's heat flow decreases in proportion to its enthalpy reduction. The heat flow (DSC) curves of SLR-1 and SLR-2 samples representing different degradation stages are shown in Figure 4. The leachate samples containing the degraded components extracted during weeks 6, 10 and 15 were compared to the fresh OFMSW (W0) originating from the landfills which was fed into the reactor columns. The graphs exhibit phase transitions caused by chemical processes such as the breakage of weak chemical linkages in diverse organic waste lignocellulosic materials, resulting in volatile chemicals in both reactor columns.

Three phases of thermal degradation of fresh OFMSW and biodegraded waste were observed in this study. In the first phase, the thermograms displays a pattern of a prominent peak in the range of 105 to 122℃, for all the samples. This corresponds to evaporation of moisture from the organic waste and in the leachate samples analysed. According to Syguła *et al*., (2021) the transformations observed at 158.0 and 177.6℃ (W10) are assigned to vitrification which appeared on thermal degradation of kitchen waste. Devolatilization of major components of the waste organic fraction and leachate are observed in the second phase. The process extends up to 310°C, with prominent thermal degradation peaks at 302.8°C (W0) for fresh OFMSW, 273°C (W10), 234°C (W15) for SLR-1 and 288°C (W10), 305°C (W15) for SLR-2, respectively. The release of volatiles and homogeneous combustion occur during this thermal transformation associated with hemicellulose depolymerization (Syguła *et al*., 2021) from components such as cardboard, paper and decomposition of biopolymers. The third phase was observed in the fresh organic waste at 349℃ (W0), 357.1℃ (W6) and 363℃ (W15) for SLR-1, 381.3℃ (W6), 364℃ (W10) and 402.3℃ (W15) for SLR-2, respectively. Thermal transformations are assigned to polysaccharide and lignin breakdown (Fernández *et al*., 2012).

The energy balance which determines the amount of energy transformations occurring during the thermal conversion process of tested organic waste shows that the reactions are divided into exothermic and endothermic reactions. The three transformations that occurred in the thermal analysis of fresh organic waste included exothermic reactions only (-117.1 J/g), (-1.2 J/g) and (-11.0 J/g). The energy balance of the transformation of the OFMSW was negative (-129.3 J/g). In SLR-1, the energy balance of the conversion during W6, W10 and W15 of degradation was -363.2 J/g, -185,51 J/g and -271 J/g, respectively. The energy balance of the transformations in SLR-2 were -206.8 J/g, -151.28 J/g and -135.72 J/g, respectively.

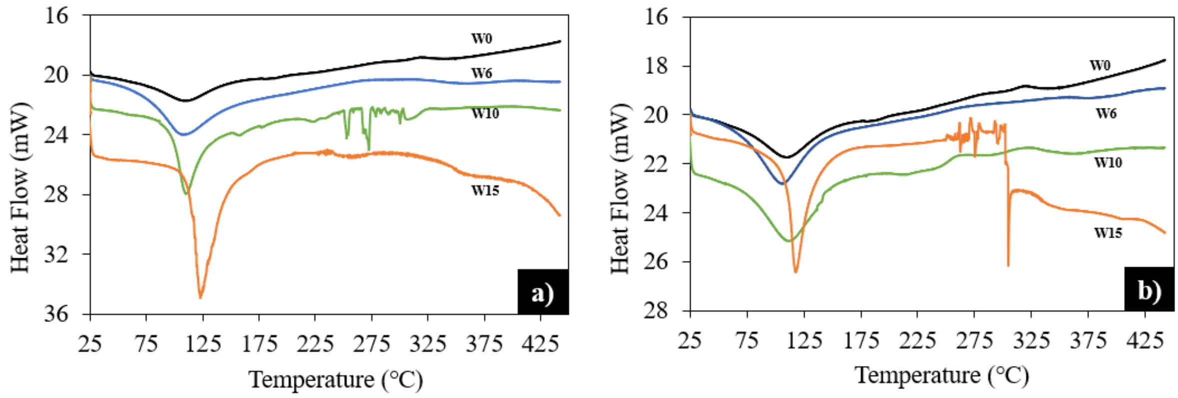

Figure 4: *The DSC thermograms from a) SLR-1 and b) SLR-2*

CONCLUSIONS

The composition of leachates provides crucial information of the status and ongoing processes in a landfill, particularly with respect to the stability of municipal solid waste organic fraction (OFMSW) and this knowledge is crucial for further implementation of strategies for the management and treatment of OFMSW to reduce its environmental impact. Hence this study focused on the application of analytical and conventional techniques to evaluate the biodegradation of OFMSW through the use of a hybrid system (partial aeration and leachate recirculation) and characterization thereof. The leachate recirculation and partial-aeration technique has been shown in the study to rapidly degrade organic matter during the hydrolysis acidification stage. Parameters such as pH, OM, and COD were evaluated and showed a strong relation to the decomposition state of OFMSW with values reaching 7.89, 19 % and < 500 mg/L, respectively, at the end of the experiments for SLR-2. Based on the FTIR analysis, the state and stability of OFMSW can be assessed through the appearance and disappearance of distinct bands such as 2920, 2850, 1030 cm^{-1} and appearance of the nitrate band at 1385 cm-1 towards stabilization and maturation. Whereas the thermal transformations in the DSC analysis, indicated wider possibilities of understanding the transformations occurring during thermal treatment of waste. Subsequent research endeavours aim to assess the potential for producing and utilizing sustainable energy through this hybrid strategy, hence potentially benefiting the local population residing in the vicinity of the dumps.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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INVESTIGATING WATER CONSERVATION STRATEGIES IN GAUTENG PROVINCE: SUSTAINABLE WATER MANAGEMENT IN BUILDINGS

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1. ABSTRACT

Gauteng Province faces significant issues related to water shortages and the need to reduce the demand for water resources, making sustainable water management in buildings an important concern. It is important to prioritize proactive demand management and water conservation measures to ensure a sustainable water supply in the future. Failure to do so could lead to resource scarcity and water shortages. The main objective of this research was to examine water conservation strategies that are especially suited for the Gauteng Province. The project aimed to find and assess efficient methods and tools buildings can employ to encourage water conservation and reduce waste. A mixed-methods research design was used, integrating qualitative evaluations with quantitative analysis. Data on water consumption patterns, conservation measures, and building attributes are gathered through surveys and interviews with building occupants, facility managers, and water utility suppliers in various parts of Gauteng Province. The province of Gauteng's population was found to know very little about water conservation; just 9% of people knew about it, and 91% didn't know how important it was. A clear reminder of the significance of appropriate water management is provided by the average of 582,901 liters of water used daily by Sedibeng, Johannesburg, Tshwane, and Ekurhuleni municipalities. The study results show that water usage can be greatly decreased without sacrificing user comfort by installing water-efficient equipment like low-flow toilets and faucets. Future research will investigate the significance of increasing awareness and creating a behavioral model for change among building inhabitants via water conservation initiatives and educational efforts.

Keywords: *Sustainable Water Management, Water Conservation Strategies, Building*

1. INTRODUCTION

The sustainable management of water resources is a paramount concern in the face of growing urbanization and environmental challenges. In this context, buildings play a pivotal role as significant consumers of water and contributors to local water stress. This research aims to delve into the "Sustainable Water Management in Buildings" realm by comprehensively investigating water conservation strategies within Gauteng Province. Gauteng province, a highly populated province in South Africa, offers a distinctive case study because of its expanding metropolitan areas and rising water resource demands. Population expansion, climate change, and the need to relieve pressure on current water supplies all highlight the need for sustainable water management techniques. Buildings are a strategic emphasis since they are vital parts of urban infrastructure and play a key role in adopting water-efficient practices.

Buildings and external envelopes are generally impervious, and their runoff can be captured and stored for reuse. In addition, most buildings are set upon paved and impervious substrates. The flow from the rooftop's external curtains and paved areas is normally channeled to the stormwater reticulation system. Here, the water is further contaminated, requiring further processing. It could be advantageous for building owners to capture this water run and recycle and reuse it. Generally classified as grey water, it can also be combined with baths, basins, showers, and zinc water. With minimum intervention, this water could be re-used and re-energized to drive toilet flushing and landscape irrigation, thereby reducing the demand for and load of potable water. The treatment and processing of this re-captured water is the domain of the Engineer, and rightly so.

The present study aims to investigate the various water-saving measures applied in buildings throughout the province of Gauteng. This study investigates strategies, from behavioral modifications to technology interventions, to determine the most useful and appropriate for the situation. Water-efficient plumbing systems, rainwater collection, greywater recycling, and the incorporation of sustainable architectural design concepts are all included in these measures. Understanding these factors and assessing the impact of different water conservation strategies is crucial for developing evidence-based guidelines and recommendations to optimize sustainable water management in buildings across Gauteng (Melita and Nina, 2012). This research is important because it could lead to better building water usage, but it's also important because it can help with more significant water resource management initiatives. To pursue a more water-resilient future, urban planners, architects, legislators, and environmental advocates can make well-informed decisions thanks to the findings. Through this exploration, we aspire to contribute meaningfully to sustainable water management discourse, fostering a harmonious balance between human development and ecological preservation.

2. LITERATURE REVIEW

Despite being the nation's smallest land area, Gauteng Province in South Africa houses the extensive Gauteng City Region. This region has approximately 14.8 million residents, constituting 25.5% of the national population. Despite its size, this province plays a crucial role in South Africa's economy, contributing significantly to the gross domestic product (around 37%). It is the country's central hub for finance, commerce, industry, and government activities (Bohenksy et al., 2004). The Integrated Vaal River System, on which Gauteng heavily relies, sustains nearly 50% of South Africa's GDP and provides resources supporting various economic activities in neighboring catchment regions. These activities include power generation, industries such as SASOL, mining operations, and the development of urban settlements (Bohenksy et al., 2004). Between 2012 and 2017, the population of Gauteng experienced a notable increase of over 1,700,000 individuals, marking one of the highest growth rates in South Africa (see Table 1). Chiu et al. (2015) carried out simulations using a geographic information system (GIS) through a case study based on eight communities in the hills of northern Taiwan to find the optimum volume of RWHS reservoir, in addition to determining water and energy savings from these systems. Gado and El-Agha (2020) studied 22 cities in Egypt and found that the potential to meet future water needs (from 2015 to 2037) ranged from 0 to 12% (Table 2), i.e. there were some cities in which the potential of RWHS to meet water needs of the city was insignificant because the amount of annual precipitation in these locations was very negligible. The many water-saving techniques frequently employed in commercial buildings were covered by Smith (2021). The author highlighted Several water-saving techniques, including using smart water meters, low-flow fixtures, rainwater collection, and greywater recycling. In their 2019 study, Johnson and Brown examine how water-efficient fixtures affect home water. The research investigates the relationship between socioeconomic variables, including household size and income levels, and how well water-efficient fixtures work to cut down on water use. Johnson and Brown (2019) conclude that installing water-efficient fixtures can help residential structures use less water. Nonetheless, they stress that attaining lasting water savings also heavily depends on the actions of locals and other socioeconomic considerations.

Table 1: StatSA midyear population estimates for District and Metro Municipalities at 5-year intervals (2002-2017)

	2002	2007	2012	2017
Sedibeng	809 188	824 663	850 853	931 516
West Rand	764 970	807 789	862 622	932 708
Ekurhuleni	2 577 466	2 879 562	3 217 535	3 576 816
Johannesburg	3 379 888	3 968 317	4 652 597	5 396 564
Tshwane	2 232 789	2 563 398	2 955 463	3 440 748
TOTAL GAUTENG	**9 764 301**	**11 043 730**	**12 539 071**	**14 278 351**
5 Year population growth		1 279 428	1 495 341	1 739 281

Furthermore, Anderson and Davis (2020) provided an extensive review of rainwater harvesting systems, emphasizing their design aspects and performance within the framework of sustainable water management in buildings. The study assesses the performance of rainwater harvesting systems by considering various parameters, such as system efficiency, water quality, reliability, and long-term maintenance requirements. They also explore the impact of climate and geographical factors on system performance. Smith (2021) explores sustainable water management practices within commercial buildings. The study focuses on the implementation and impact of these practices.

The study by Patel and Gonzalez (2018) presents a cost-benefit analysis of greywater recycling systems in commercial buildings. Greywater recycling involves treating and reusing wastewater from activities like bathing and laundry. The key findings and themes explored in their research are as follows: The study's primary objective is to assess the cost-effectiveness and benefits of implementing greywater recycling systems in commercial buildings, emphasizing water conservation and economic considerations. Gleick (2003) discusses the global trends in water consumption, emphasizing the significant increase in water demand over the 20th century. He highlights that this growth is outpacing the natural replenishment of freshwater sources. The study by Hwang and Liu (2021) investigates the crucial role of government policies in promoting sustainable water management practices within buildings. The research focuses on how policy measures can drive and facilitate water conservation and efficiency in the built environment.

3. METHODOLOGY

In these cases, two main methods were applied: deductive and inductive. An inductive research approach aims to test a theory, which is the main difference between inductive and deductive reasoning. An inductive research technique was employed to examine water conservation strategies in structures in Gauteng Province. Inductive research gathered and analyzed data to find patterns, themes, or ideas based on observations.

3.1. Research Strategies

Statistical techniques were applied in quantitative research to collect and analyze numerical data. It aimed to produce factual, objective data that could be measured and expressed numerically. In contrast, non-numerical data from sources like text, images, and audio were collected through qualitative research. Focused on exploring subjective experiences, opinions, and attitudes, it frequently employs techniques such as interviews and observation. A mixed-methods strategy was used for this study. Integrating quantitative and qualitative research methods is a key component of the mixed-method approach used to study water conservation measures for sustainable water management in buildings in Gauteng Province. This method made an extensive grasp of the intricate elements and difficulties related to water conservation possible.

3.1.1. Data collection and analysis procedures and tools

3.1.1.1. Data Collection

Primary Data

Surveys: Structured questionnaires administered to building occupants to assess their awareness, attitudes, and behaviors regarding water conservation practices.

Interviews: Semi-structured interviews were conducted with building owners, facility managers, and water service providers to explore their perspectives, challenges, and experiences with sustainable water management in buildings.

Site Visits: On-site observations were conducted to gather data on selected buildings' water fixtures, systems, and infrastructure.

Water Usage Data: Water consumption data is collected from utility bills or water meters to analyze patterns and trends.

Secondary Data

Literature Review: A comprehensive review of existing literature, policies, regulations, and case studies related to sustainable water management and water conservation in buildings within Gauteng Province will be conducted.

Data from Government and Non-Governmental Organizations: Secondary data sources such as reports, guidelines, and publications from relevant government departments and organizations will be analyzed to gain insights into the policy and regulatory landscape.

3.1.1.2. Data Analysis

Quantitative Data: Statistical analysis of survey data using appropriate statistical software to examine patterns, trends, and relationships between variables. Descriptive, correlations, and inferential statistics are used to analyze the quantitative data.

Qualitative Data: Thematic analysis is employed to analyze interview transcripts and open-ended survey responses—themes and patterns related to water conservation strategies, stakeholder perspectives, challenges, and opportunities identified.

The aim of data collection and analysis procedures and tools for "Sustainable Water Management in Buildings: Investigating Water Conservation Strategies in Gauteng Province" was to systematically gather, process, and interpret data to achieve the research objectives related to water conservation strategies in buildings.

3.1.2 Ethical Conduct

Ethical conduct was fully respected and applied during the survey by handing the structured questionnaires to the targeted group.

4. RESULTS AND DISCUSSIONS

Water consumption patterns vary among different types of buildings. Residential buildings tend to have more consistent water usage patterns, while commercial and industrial buildings exhibit fluctuations in demand. Questionnaires (521) of water consumption were collected during the data collection process and were randomly distributed in Figure 1 below.

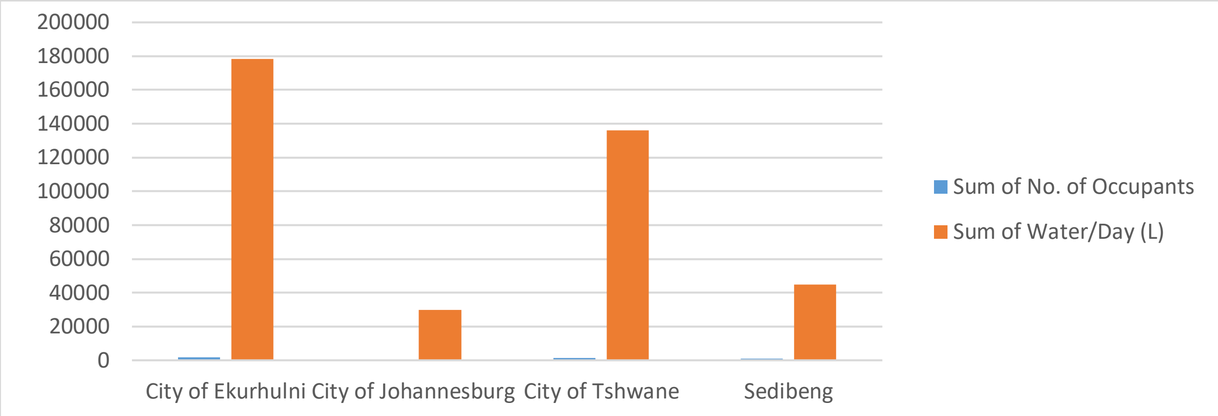

Figure 1: Water consumption

The data provided in Figure 1 offers a significant insight into water consumption across several municipalities. The total number of occupants in the City of Ekurhuleni, City of Johannesburg, City of Tshwane, and Sedibeng combined is 3,895, and their collective daily water consumption amounts to 389,500 liters. This information underscores the substantial water demand within these urban areas, necessitating a continued focus on water resource management and conservation strategies to ensure sustainable water usage. These municipalities must adopt measures that meet the current water needs and address the challenges of population growth and increasing demands in the future. Water conservation and efficient management practices are critical to preserving this precious resource for the well-being of current and future generations. Implementing efficient water conservation and demand management systems is becoming increasingly important as these communities continue to grow and urbanize to guarantee the sustainability of water resources. This data emphasizes that to fulfill the increasing water demands in these locations, careful planning, the development of infrastructure, and adopting sustainable practices are necessary. To ensure a steady water supply in the future, taking preventive steps now is crucial because failing to do so could lead to a shortage of resources and water. Figure 2 compares water use by residential, commercial, and industrial categories.

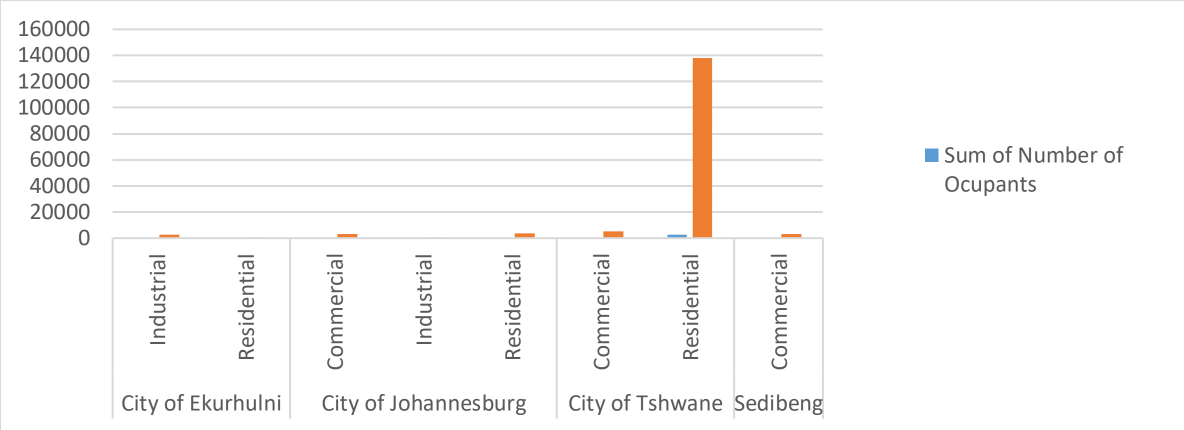

Figure 2. Water consumption breakdowns

It is evident from the analysis of Figure 2 water consumption data for the several municipalities in the region that there is a sizable and varied demand for water. These numbers provide a thorough picture of the water requirements in various industries and regions. With considerable demands from the residential and commercial sectors, the City of Tshwane stands out as the greatest user, illustrating the complex nature of urban water management. Even though the commercial and industrial sectors use much water, the data emphasizes how important it is to implement water conservation measures. To maintain the sustainability of our water resources and meet the increasing water needs of our communities, we must emphasize effective water usage and water demand management techniques in the future. With a total daily water usage of 582,901 liters, it is clear from the statistics in Figure 3 that the municipalities of City of Ekurhuleni, City of Johannesburg, City of Tshwane, and Sedibeng consume a significant amount of water. These numbers demonstrate the substantial demand for water resources in various commercial, industrial, and residential industries.

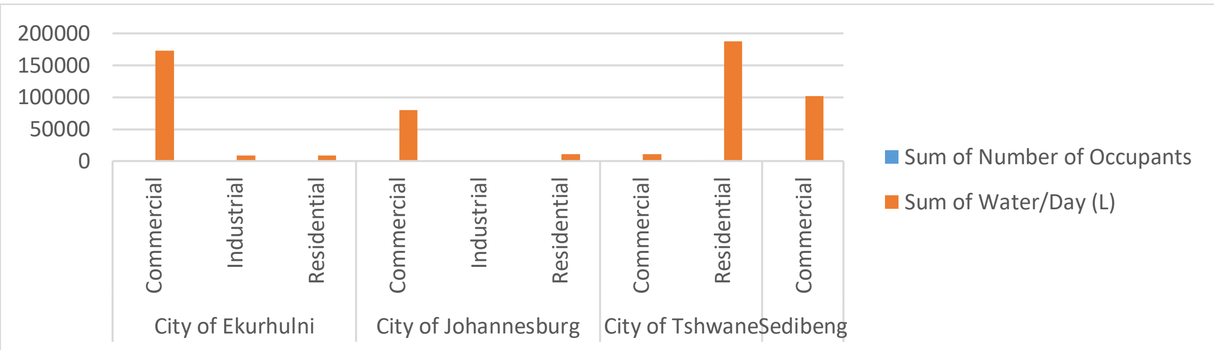

Figure 3: Variation of water demand in municipalities

The sustainable use of water is contingent upon managing and conserving water resources, especially in places such as these municipalities with a high population density and various industries. Maintaining an equilibrium between the growing demand and the finite water supply requires focusing on demand management and conservation techniques. To further address the issues brought on by urbanization and the expansion of industry, it highlights the significance of effective resource management and water allocation.

The data provided is reflected in Figure 3 in the water consumption patterns across various municipalities within the Gauteng region. It is evident that different sectors, including residential, commercial, and industrial, contribute significantly to overall water usage. The City of Ekurhuleni, the City of Johannesburg, the City of Tshwane, and Sedibeng exhibit diverse demands for water resources, with residential areas usually consuming a substantial portion of the water supply. Efforts to manage and conserve water resources, particularly in residential and commercial sectors, are paramount. The cumulative water consumption figures, totaling 353,320 liters per day, underscore the need for proactive water conservation measures and sustainable practices to ensure the long-term availability of this vital resource. Addressing water sustainability and promoting responsible water usage across all sectors will be crucial for the future, ensuring that we can meet the growing demands of these municipalities without compromising the availability of clean and safe water resources.

4.1. Correlation Analysis

A correlation coefficient r = 0.74 measures the strength and direction of the linear relationship between two variables. In this context, with two variables:

a. Number of occupants: This represents the number of people occupying a Residential, Commercial, and Industrial building.

b. Water consumption per day in litters: This represents the daily water used, typically measured in litters.

The correlation coefficient of r = 0.74 indicates a moderately strong positive linear relationship between the number of occupants and daily water consumption. This means, in summary:

As the number of occupants increases, the daily water consumption also tends to increase.

Table 2: Correlation Table

c	No. of Occupants	Water/Day (L)
No. of Occupants	1	0,74
Water/Day (L)	0,74	1

The positive correlation suggests that when more people are present, there is a tendency for higher water usage. This is a reasonable expectation as more people generally increase water needs for drinking, sanitation, and various activities.

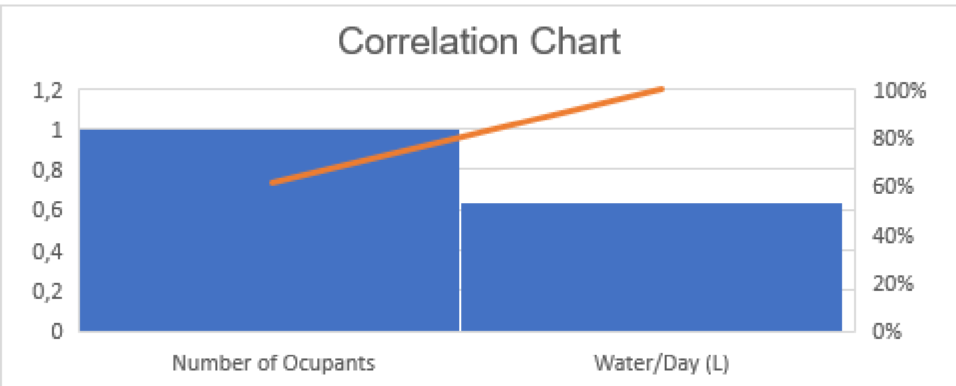

Figure 4: Correlation chart

In summary, the correlation coefficient of r = 0.74 indicates a positive relationship between the number of occupants and daily water consumption, suggesting that as the number of occupants goes up, water usage tends to increase.

4.2. Awareness of Water Conservation in Gauteng

The purpose of the survey was to gather information on public knowledge of water conservation so that policymakers could decide whether to launch a campaign in each municipality to inform the public about the importance of water conservation.

Table 3: Awareness of Water Conservation

Count of Yes	48	9%
Count of No	473	91%
Sum of Participants	521	

The above diagram shows how the people from Gauteng province are not aware of the effectiveness of water conservation. Moreover, more campaigns should regularly take place in all 5 municipalities in Gauteng Province. The table summarizes the awareness of water conservation in Gauteng province among 521 participants. Of the participants:

- 48, or approximately 9%, answered "Yes" when asked about their awareness of water conservation.
- 473, or about 91%, answered "No" to the same question.

This table provides an overview of the survey's responses regarding awareness of water conservation, with most participants indicating that they are unaware.

4.3. Calculation of the mean, median and standard deviation

Table 4: Calculation of the mean, median, and standard deviation.

Water/Day (L)	
Mean	8983,051923
Standard Error	1055,297864
Median	1500
Mode	400
Standard Deviation	24064,49382
Sample Variance	579099862,8
Kurtosis	67,27354268
Skewness	6,72559902
Range	285985
Minimum	15
Maximum	286000
Sum	4671187
Count	520
Confidence Level (95,0%)	2073,180493

These statistics provide insights into the dataset's distribution and characteristics of daily water consumption, including central tendency, variability, and distribution shape.

Table 4 shows the values of the mean, median, and standard deviation, and this is where the result will be used for further investigation

The provided statistics describe a dataset in Table 3 related to daily water consumption (measured in litters). The dataset consists of 520 data points. The mean (average) water consumption is approximately 8,983.05 liters per day. The standard error is about 1,055.30 liters. The dataset's median (middle value) is 1,500 litters, while the mode (most common value) is 400 litters. The standard deviation, which measures data spread, is approximately 24,064.49 liters. The sample variance is about 579,099,863 liters squared.

4.4. Cause and Effect of water scarcity in Gauteng Province

During the data analysis, the fishbone diagram was used to determine the exact cause and effect of water scarcity in Gauteng Province.

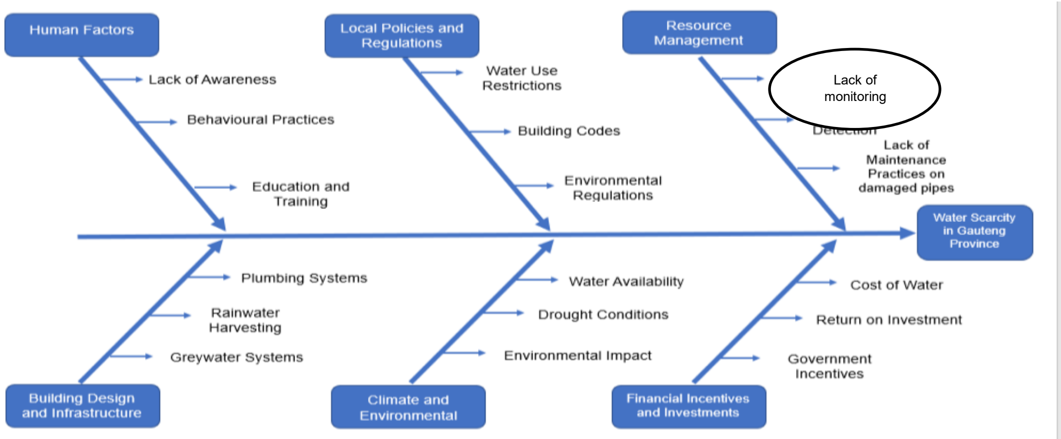

Figure 5 Fishbone Diagram

In the context of sustainable water management in buildings and investigating water conservation strategies in Gauteng Province, a fishbone diagram helped structure and categorize the factors contributing to the problem or challenge of water conservation.

The Fishbone Diagram highlights the multifaceted nature of water conservation challenges in Gauteng Province's buildings. The factors contributing to sustainable water management issues encompass various aspects of the environment, infrastructure, resources, human behavior, financial considerations, and regulatory frameworks. The interconnectedness of these factors emphasizes the importance of a holistic approach to address the problem effectively.

Solutions should target each of these categories to improve sustainable water management. This could involve implementing climate-resilient building designs, upgrading infrastructure with water-efficient technologies, enforcing water conservation regulations, promoting water-saving behavior among building occupants, and offering financial incentives and investments in sustainable water projects. By addressing the causes within each category, a comprehensive and integrated approach can be developed to ensure more effective water conservation strategies and, ultimately, better sustainable water management in buildings across Gauteng Province.

5. CONCLUSIONS

Many important elements significantly impacting water conservation techniques have emerged because the Gauteng Province investigated Sustainable Water Management in Buildings. According to the findings, successfully achieving sustainable water management in buildings requires addressing three significant challenges: high water usage, poor education, and lack of awareness. One major obstacle was the lack of knowledge about the significance of water conservation among building tenants and stakeholders. Water conservation techniques in buildings in Gauteng Province can only be successfully implemented if the problems of low awareness, poor education, and excessive water usage are addressed. This study combined quantitative and qualitative research methods to present a thorough picture of water conservation issues and possible solutions. This highlights the significance of taking a complete approach to sustainable water management. These fixtures could significantly reduce water use without sacrificing user comfort. The study recommends promoting water-efficient plumbing installations in structures, including low-flow toilets, water-conserving faucets, and high-efficiency showerheads. Future research will create a framework to support a sustainable water recovery plan outside South Africa's rural areas, including Gauteng Province.

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SUSTAINABLE WATER SUPPLY IN SUB-SAHARAN AFRICA: CHALLENGES, ADVANCEMENTS AND PERSPECTIVES.

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ABSTRACT

Access to clean and safe water is a primary factor that directly influences sanitation, hygiene, and general human health. Inadequate access to clean and safe water resources is a leading risk factor for waterborne diseases, such as diarrhoea, which is one of the primary causes of mortality and disability-adjusted life-years (DALYs) on a global scale. However, the water and sanitation conditions are growing ever more fragile worldwide. Rapid population growth, continuous urbanization, and growing water demands from the energy, industrial, and agricultural sectors have resulted in a sharp rise in demand, while climate change is diminishing the availability of fresh water. Furthermore, water quality is continuously depreciated by water pollution. Whereas global initiatives such as the Sustainable Development Goal (SDG)6 have paved the way for much progress in providing safe and clean water, and improving sanitation to the masses, developing nations, notably those in sub-Saharan Africa (SSA), face considerable challenges in achieving this goal. Therefore, this paper presents a comprehensive overview of the water accessibility status in SSA countries. Impeding challenges including climate change, limited water resources, water pollution, and poor governance are summarised. Up-to-date progress made in ensuring clean water availability is highlighted. The broader implications of water scarcity on human health, the environment, and the economy are discussed. Perspectives and recommendations for sustainable water supply, in SSA are given.

Keywords: *Water and sanitation, water scarcity, water stress, Sustainable Development Goals, Sub-Saharan Africa*

INTRODUCTION

The 21st century has seen most countries and major cities globally grapple with growing water scarcity challenges, regardless of economic status (Savic, 2021). According to the 2024 report of the United Nations (UN) World Water Development Agency, 2.2 billion people globally do not have available clean water and 3.5 billion lack provision to properly administered sanitation services (Aljazeera, 2024). This includes the entire population of Africa (~ 1.3 billion people), with SSA having the largest number of water-stressed countries (Ighobor, 2023). Noteworthy, SSA is currently the most impoverished and least advanced region globally. This is largely due to a combination of factors, including widespread economic development challenges, poverty difficulties, rapid population growth, and rural-urban migration. Although most countries in SSA are not currently experiencing extreme water stress, the region is witnessing a faster growth in water demand than the rest of the world (Aljazeera, 2024). By 2050, water demand in SSA is expected to rise by 163%, far above the projected 43% increase in Latin America, representing the second-highest global increase (Wikipedia, 2023).

Water scarcity in Africa including SSA stems primarily from physical and economic factors (Wikipedia, 2023; Mlaba, 2022). Physical scarcity manifests when a region's water demand exceeds available water resources and occurs seasonally (Genesis, 2023). On the other hand, the main causes of economic water scarcity are either the absence of water infrastructure or inadequate resource management in regions where infrastructure exists (Genesis, 2023). The

Food and Agricultural Organization (FAO) of the UN reports that approximately 1.6 billion people experience economic water crisis worldwide, whereas 1.2 billion, mostly in arid or semi-arid countries, live under physical water scarcity (Petruzzelo, 2024). The agenda for 2030 Sustainable Development, endorsed in 2015 by all UN member states, provides a framework structure for addressing global water challenges through SDG6 (ensuring universal availability of clean water and sanitation) (UN, n.d.). However, as global efforts advance towards realizing SDG 6, Africa is regrettably the only region lagging with millions of people, particularly in SSA still lacking this basic resource. In 2020, approximately 387 million people in SSA did not have available clean drinking water, whereas 737 million and 811 million lacked basic sanitation and hygiene services. Furthermore, about 50% of schools and healthcare facilities lacked adequate water and sanitation services (Ayat and Saroj Kumar, 2023). Although some significant improvements in water provision have been achieved in some major cities in SSA, they still fall far short of the SDG6 goals, (Wikipedia, 2023; Fontana, 2022). According to the Global Water Security 2023 Assessment report, major contributors to water insecurity in SSA include population and economic growth, conflicts, and the impacts of climate change (Ighobor, 2023). Additionally, water challenges in SSA are exacerbated by inequitable water resource allocation and distribution, lack of/underdeveloped urban infrastructure, poor governance, and a lack of political will to tackle the rising challenge of water scarcity (Wikipedia, 2023).

The impacts of water scarcity in SSA reach beyond the directly affected population, given that agriculture is a major part of the economy in Africa, accounting for 95% of global rainfall-dependent agriculture (ADB, 2024). When water shortages affect agricultural production, many people's livelihoods are jeopardized and serious repercussions on the economy are manifested (Bensen, 2022). Food security, good health, social stability, and other essential needs become a luxury many people, especially the poor cannot afford. Eradicating water insecurity in SSA is therefore of paramount importance. However, this would require an integrated multidisciplinary approach encompassing all stakeholders, including policymakers, scientists, and funding agencies. This paper aims to provide an updated overview of water accessibility in SSA. Water scarcity drivers and water supply challenges are reviewed and discussed. Up-to-date progress made in clean and safe water provision is evaluated. Perspectives and recommendations for sustainable water supply in SSA are given.

WATER ACCESSIBILITY CHALLENGES

Inequitable water resource distribution

Water accessibility varies significantly within SSA. This is mostly due to the unequal distribution of water resources, with only six nations controlling 54% of Africa's water, while 27 water-stressed SSA countries share a mere 7% (Nkatha, 2024). For example, about 589 of the 980 major dams in SSA are located in South Africa, while Tanzania, a country of similar size and population, has only two large dams (Nkatha, 2024). In some cases, a smaller population resides in areas with abundant water. This is the case with the Congo Basin, which holds 30 percent of the continent's water and is home to only 10 percent of Africa's population (Lai, 2022). Furthermore, despite plentiful rainfall in SSA, it is seasonal and irregularly distributed making floods and drought common. Somalia is one such country, most severely affected by water shortages due to unpredictable floods and protracted droughts that diminish their groundwater supplies (USAID, n.d.). On the contrary, other regions of SSA have high evaporation rates, leading to lower precipitation levels in those areas (Lai, 2022). Nonetheless, water insecurity in SSA is generally caused by both physical and economic factors, as already highlighted. Figure 1 depicts water unavailability in Africa due to physical and economic factors.

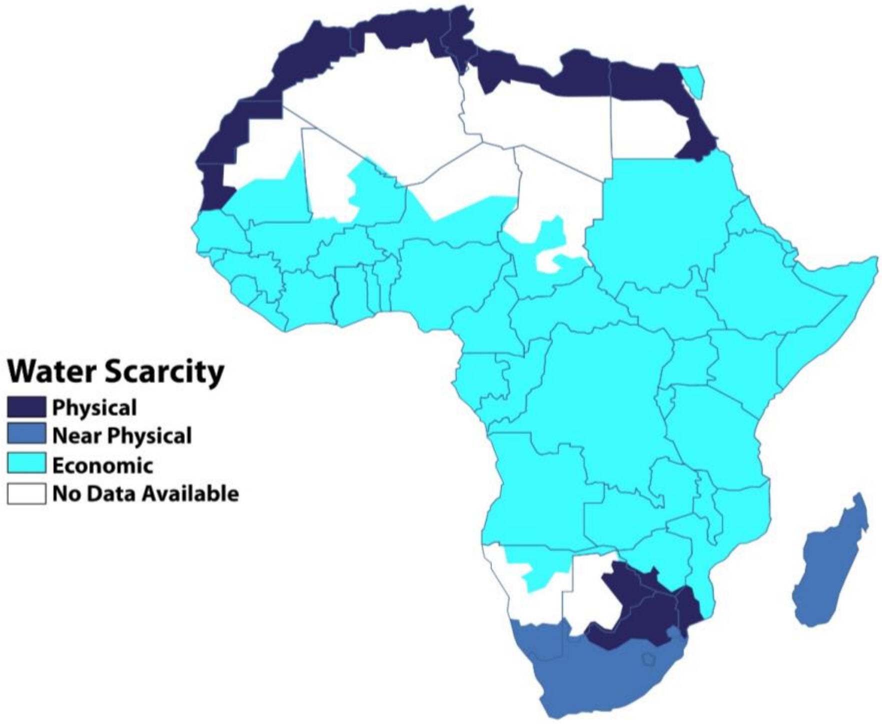

Figure 1: *Water scarcity in Africa due to physical and economic factors.(Genesis, 2023)*

From Figure 1, water scarcity in SSA is primarily due to economic factors, except for a few parts of Southern Africa where physical factors dominate. Many African countries have plentiful groundwater reserves, sufficient to withstand at least five years of drought, according to research released in 2022 by WaterAid and the British Geological Survey. However, people living in a country or region with plentiful water resources may still suffer water insecurity because of mismanagement (Nkatha, 2024). This is seen in Malawi, where there are thirteen rivers that flow year-round and three lakes, including Lake Malawi, which is ranked the world's fourth-largest freshwater source by volume. Despite this wealth of resources, their potential role in mitigating hunger during droughts is largely overlooked in the country's developmental strategies (ohchr, 2020). The situation in the Congo Basin presents a similar case to Malawi. The Congo Basin stretches across six countries (Cameroon, Central African Republic (CAR), Democratic Republic of the Congo (DRC), Republic of Congo, Equatorial Guinea, and Gabon), yet all struggle with water accessibility problems (Fontana, 2022). The worst affected are DRC and CAR, with 54% of the population in DRC lacking basic water services (Reid, 2023). This is despite the location of DRC within the heart of the Congo Basin, giving it access to the largest freshwater resources in Africa. Over half of CAR's population of ~ 4.9 million is in dire need of water, with water scarcity rated high (Concern Worldwide, n.d.). A shared challenge among these countries is the non-existent or deteriorating water infrastructure, exacerbated by inadequate investment in the water sector, political instability and damage from protracted conflicts, rapid population growth, and extreme poverty (Fontana, 2022)(Concern Worldwide, n.d.). DRC is also on the top 10 list of the worst affected SSA countries, which includes Niger, Chad, Uganda, Eritrea, Ethiopia, Somalia, Angola, Mozambique, and Malawi (Reid, 2023). This list is based on the 2020 projections from the Joint Monitoring Programme (JMP) of the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), which oversees the maintenance of worldwide data on improvements in clean water, sanitation, and hygiene (WASH)

As much as progress has been made in some countries to afford clean and safe water to a wider population, the vulnerable groups, mostly in informal settlements and rural areas are still left behind. Approximately 39% of the people in SSA have water connected to their households, whereas this figure drops to about 19% in rural areas (Fontana, 2022). Noteworthy, the rural population often constitutes the majority of people in SSA. Figure 2 compares water accessibility in various countries across SSA. The data shows water on-site, which refers to water connected directly to a person's residence or a building.

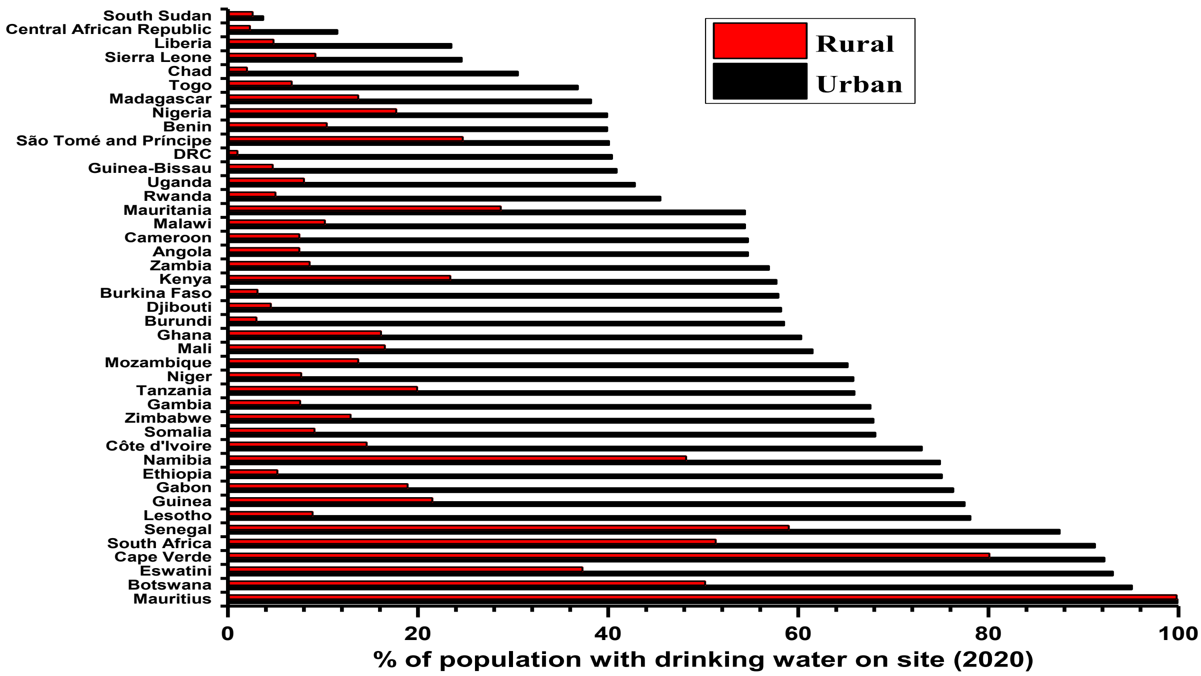

Figure 2: *% Population with drinking water on site (2020)*

Generally, there is a wide gap between urban and rural water provision across SSA, except for Mauritius with almost 100% water and sanitation provision for its entire population (Figure 2). To achieve this milestone, the government of Mauritius invested extensively in water mobilization projects including borehole drilling, construction of new dams, service reservoirs, water treatment plants, and upgrading existing ones (ohchr, 2020). Lessons could be drawn from Mauritius's effective water management to mitigate the water crisis in other parts of SSA. Despite harbouring one of Africa's largest freshwater reserves, DRC has the least rural population (1%) connected to water in their households (Figure 2). Water access in the urban areas is relatively low, at less than 50%. On the other hand, Ethiopia exhibits the greatest disparities within a single nation, only 5% of rural Ethiopians have water in their residences compared to 75% in urban communities (Figure 2). South Sudan has the poorest water provisions, both in rural (2.6%) and urban (3.7%) populations (Figure 2). The trend shown in Figure 2 could be attributed to a combination of physical and economic factors, as will be discussed further in the following sections.

Climate change and political conflicts

Africa, particularly SSA is the most susceptible region to the impact of climate change (ADB, 2024). Despite its minimal contribution to global warming and lowest emissions, SSA experiences disproportionate collateral damage from climate change. Climate change predictions for SSA indicate a warming progression, particularly in the inland subtropical region, with more frequent extreme heat events, growing aridity, and shifts in rainfall patterns (Crisis Watch, n.d.). Southern Africa is anticipated to experience a notable decrease in rainfall, while East Africa is likely to have an increase (CDP, 2024). Studies postulate that by the year 2050, rainfall in SSA could decrease by 10%, potentially leading to severe water scarcity (Lai, 2022). Long-term consequences include erratic rainfall patterns affecting agriculture and diminishing food security, declining fish reserves in lakes due to rising temperatures, increased prevalence of vector-borne and water-borne diseases, rising sea levels impacting densely populated low-lying coastal regions, and escalating water scarcity (Wikipedia, 2023; Reid, 2023; Crisis Watch, n.d.). On the other hand, floods triggered by heavy rainfall threaten water supplies through infrastructure damage, heightened water source pollution, and drainage system impairment. Inundation of sanitary infrastructure by floodwaters can result in sewage overflows and the transmission of water-borne diseases. Water bodies may get further contaminated by pollutants carried in floodwaters from industrial sites, metropolitan regions, and agricultural lands. World Health Organization (WHO) has since declared climate change the biggest threat to global health in the twenty-first century due to its immense contribution to the already dire water crisis in SSA and worldwide (Savic, 2021).

The effects of climate change are well demonstrated in the Horn of Africa, including Ethiopia, Kenya, Somalia, and South Sudan. The provision of sustainable water supplies in this region is made more challenging by unpredictable rainfall patterns, floods, and severe periodical droughts (Reid, 2023). Currently, the region is experiencing the worst drought in decades, after five consecutive years of lower-than-normal rainfall (CDP, 2024). The humanitarian crisis is further exacerbated by extreme poverty, economic shocks, disease outbreaks, ongoing conflicts, and other regional instabilities in the Horn of Africa (Bensen, 2022; USAID, n.d.). Furthermore, the projected 2024 El Niño season is expected to deliver downpours to the region’s climate-vulnerable areas, including Ethiopia and Somalia (CDP, 2024; Relief Web, 2024). Some of these locations already endured prolonged flooding from September 2023 to March 2024 (Crisis Watch, n.d.). Thus, more flooding could further diminish water security, and promote the proliferation of vector-borne and water-borne diseases, worsening the prevailing cholera outbreak. Due to the dual risks of conflict and El Nino-triggered flooding, Ethiopia is currently listed on the International Rescue Committee (IRC)'s 2024 Emergency Watchlist (Crisis Watch, n.d.). In 2022, South Sudan was classified as the most climate change-vulnerable country among the world’s top politically volatile nations (World Bank Group, 2023). The absence of climate-resilient water systems in countries such as South Sudan raises their susceptibility to floods. The 2020-2022 floods in the country impacted about 1.2 million South Sudanese, displacing more than 300,000 and racking up $671 million in economic losses (World Bank Group, 2023). Additionally, countries like Kenya face elevated risks of rising sea levels, landslides, and mudslides during floods, resulting in water pollution.

On the contrary, extended periods of below-average rainfall result in the depletion of about 90% of borehole water in the Horn of Africa. In Kenya, this phenomenon led to the drying up of ~ 95% of water sources in Marsabit and Turkana (Nkatha, 2024). Consequently, unregulated water markets emerged, where vendors sold low-quality water and increased prices arbitrarily. Generally, water shortages in the Horn of Africa have forced most people to buy water from vendors, despite the associated health risks (Ighobor, 2023). Moreover, drought has ravaged agriculture, resulting in critical food shortages (Bensen, 2022). Thus, food and water prices have skyrocketed rendering them unaffordable to many. Overall, the humanitarian crisis in the Horn of Africa is causing severe food shortages and malnutrition, public health problems, extreme poverty, and displacement of millions of people. About 7 million children in the region are malnourished, and 1.5 million people have been displaced. (Bensen, 2022). Interestingly, the World Weather Attribution (WWA) report, 2023, asserted that drought in the Horn of Africa would not have occurred, were it not for climate change (Kaliza, 2023). Thus, demonstrating the major role played by climate change in SSA's water insecurity.

The devastating effects of climate change are echoed in Southern Africa. Contrary to the Horn of Africa, the crisis in Southern Africa could be largely ascribed to the El Nino phenomenon, characterized by rising temperatures and an extreme lack of rainfall (Kaliza, 2023). Between October 2023 and March 2024, El Nino has steadily intensified across Angola, Botswana, Namibia, Zimbabwe, Zambia, Mozambique, southern Madagascar, and some parts of the Zambezi basin, resulting in extreme drought (Joint ResearchCentre, 2024). 70% and 80% of harvests have been destroyed in Zambia and Zimbabwe, respectively (EWN, 2024). Consequently, Malawi, Zambia, Zimbabwe and Lesotho have declared states of emergency, with Angola and Mozambique expected to join soon (EWN, 2024). Oxfam reports that an increase in the El Nino effects is worsening the ongoing dry spells in southern Africa leading to extended droughts (Kaliza, 2023).

Particularly susceptible to the climate shifts, is agriculture, with ~ 90% of cultivated land in Southern Africa dependent on rainwater (Lai, 2022). The harsh conditions have manifested diminished soil moisture, depleted groundwater, vegetation stress, crop failure, and disrupted food-growing seasons. This has led to acute food insecurity and rising food costs, impacting 27 million people across most parts of Southern Africa (Joint ResearchCentre, 2024). FAO and the World Food Programme (WFP) have projected that poor harvests following 14 severe droughts in the last two decades will leave 27.4 million people in Southern Africa more prone to hunger than any other continent within six months (Kaliza, 2023). Furthermore, the electricity supply is under strain as hydropower generation grapples with water supply shortages, particularly in countries heavily reliant on hydropower. While elevated risks of wildfires poses additional challenges for Botswana, Namibia, and northwest, South Africa (Serdeczny et al., 2017), floods have been reported in some cases. For example, cyclones Idai and Kenneth devastated coastal Beira city and northern regions, displacing numerous families between March and April 2019. Months of flooding created an environment conducive to cholera outbreaks and other waterborne diseases.

Although some parts of Southern Africa are not yet severely water-stressed, the water situation in South Africa is increasingly becoming precarious, with major cities like Johannesburg and Cape Town facing varying degrees of water scarcity. In 2018, Cape Town experienced the worst water crisis, after three years of poor rainfall. Although climate change could be blamed, Cape Town, with a dry climate, rapid urbanization, and relatively high per capita water consumption, was evidently on course for a water crisis. The city's deteriorating water systems had long been struggling to cope with its growing population. Furthermore, as dam levels started to drop during the first two years of drought, the city officials responded with a mild call for water awareness. Obviously, the response was not enough to deter the subsequent downward spiral of the water crisis. Hence, one could conclude that the 2018 water crisis in Cape Town was compounded by a combination of inadequate planning, and poor crisis management. Nevertheless, "day zero", (when taps would run dry) was averted by the timeous rainfall preceded by a series of stringent water rationing measures (World Economic Forum, 2019). Although Cape Town and surrounding areas are currently facing serious floods due to heavy winter rains and cold fronts in 2024, the situation seems to be under control, probably due to lessons from 2018.

Another water crisis is looming in South Africa, following caution by Rand Water (the largest bulk water supplier in Africa), in its corporate business plan (July 2023 to June 2028) that it anticipated being unable to satisfy water demand in the near future (Johan Eybers, 2024). This could put millions of residents in Gauteng, Northwest, Free State, and parts of Mpumalanga, at risk of water shortages. Rand Water highlights several major challenges with its water supply. These include water scarcity, climate change, erratic rainfall patterns, deteriorating water quality due to pollution, leaks due to aging or dysfunctional infrastructure, lack of investment in the upgrades and maintenance of WWTPs, unsecured pipelines prone to vandalism, theft, and wildfires, delays in completing the Lesotho Highlands Water project, service interruptions and rising demand for water. To prevent taps from running dry, Rand Water is currently extracting more water from the Vaal River than allowed by its license. This unsustainable practice poses a long-term threat to water availability. From the Rand Water standpoint, it is clear that these water problems are not water scarcity issues but institutional failures from the policymakers, water suppliers, and municipalities. For example, Gauteng has sufficient water available, but approximately 45- 50% of the water pumped by Rand Water, is lost due to leaks before reaching consumers (Jacobs, 2024). According to (Jacobs, 2024), Johannesburg requires R25 billion to repair its water infrastructure and additional billions to replace outdated equipment, necessary to accommodate the growing population and meet the increasing water demand. Noteworthy, Rand Water is currently embarking on a 37-day maintenance drive scheduled to last till 29 July 2024 in Gauteng. One may argue that this is too little too late, considering that Gauteng is already facing a water distress. Nevertheless, reduced leakages and improved water supply could be expected from this maintenance overhaul.

Water conflicts

Disputes on the use and management of freshwater resources could intensify already-existing political tensions between states sharing transboundary water bodies such as rivers. SSA's vulnerability to potential conflicts triggered by water issues manifests distinctly across four key regions: the Nile, Niger, Zambezi, and Volta basins (Nkatha, 2024). As climate change intensifies, the Nile conflict has entered a new dimension of complexity, triggering competition among regional states (Egypt, Ethiopia, and Sudan) for water, food, and energy security. The tensions between Egypt and Ethiopia were further escalated by the commencement of the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile in 2011 (Gashaw, 2023) and subsequent filling up from 2020 to date, without agreement (Tawil, 2024). In the Niger region, spanning Guinea to Nigeria, the Niger River is crucial for Mali, one of the world's poorest nations, providing essential resources for sustenance and transport. However, its intensive use has led to severe pollution, rendering the water increasingly unfit for use (Baker et al., 2023). In southern Africa, the Zambezi River basin stands out as one of the most heavily exploited globally, pushing Zambia and Zimbabwe into fierce competition over its resources. Zimbabwe's opening of the Kariba Dam gates in 2000 caused the region's worst flooding in recent memory (Mozambique News Agency, 2001). In the Volta basin, Ghana heavily relies on the Akosombo Dam for hydroelectric power, crucial for its economic growth, yet recurrent droughts severely curtail electricity production, exacerbating regional instability and limiting Ghana's capacity to provide power to its populace (Namo et al., 2022).

An extreme case involves the split of Côte D'Ivoire into the rebel-led north and government-controlled south between 2002 and 2003 (Relief Web, 2005). The conflict resulted in unpaid water bills, which disrupted distribution, triggering a severe health crisis in the region, including an increased threat of waterborne diseases like cholera. Some analysts speculate that the disruption in water distribution was a deliberate political tactic aimed at exerting pressure on the rebel-led faction (Relief Web, 2005). In Sudan, water conflicts are a contributing factor in the humanitarian crisis, particularly the arid Darfur region. Tensions between farmers and nomadic herders over scarce water resources, and grazing areas, are the root cause of the conflict, which is exacerbated by the Sahara Desert's expansion (Schlein, 2011). Water scarcity has aggravated disputes in other regions as well, such as the CAR and the eastern provinces of the DRC (Lai, 2022)

A water permit system has been implemented in some African countries, such as South Africa, to tackle water scarcity (IISD, 2018). In such a system, consumers are only allowed access to a specific volume of water in specific areas based on local laws. However, this system often leads to heightened conflict, as water rights tend to favor large-scale irrigated farms, mining operations, and industrial facilities. Additionally, the research findings from the International Water Management Institute (IWMI), 2018 revealed that water permit regulations in Africa are penalizing small-scale farmers who cannot acquire permits (IISD, 2018). This may restrict agricultural output and hinder economic development. According to the UN, of the 153 countries sharing water resources, only 24 have established cooperation agreements that address all their shared water. Thus, creating room for conflict in those countries without agreements (UN, 2024).

Displacement caused by water problems has become widespread in African communities. The worst affected are the low-income families as they are often forced to relocate in pursuit of water. Furthermore, people whose livelihoods depend on water accessibility are also displaced as they seek more sustainable means of living. However, the displaced population places a burden on local resources in their new communities, which frequently results in disputes. This was seen in Somalia, where reports of gender-based violence against displaced individuals increased by 200% (Aljazeera, 2024). On the other hand, women and children are the most affected since the bulk of water collection often falls on them. This may hinder their educational prospects and other personal development endeavours. In Chad, where ~ 2% of the rural population has access to potable water in their households, only 14% of women are literate (Fontana, 2022). Additionally, UNESCO data from 2019 indicates that approximately 500 000 of the over 700 000 children who were out of school in 2019 were females (Fontana, 2022)

Population and economic growth

As of 2020, the population growth in SSA was projected at a rate of 2.7% annually, which is more than double that of Latin America (0.9%) and South Asia (1.2%) (Lai, 2022). Nigeria is expected to double its population by 2050, while cities such as Yaounde, Cameroon and Bamako, Mali have witnessed rapid expansion too (Lai, 2022). According to the UN, 21 out of the 30 fastest-growing cities globally were in Africa in 2018. The growing population drives increased demand for food, accelerated urbanization, and industrialization, all of which depend on a plentiful supply of water. Furthermore, as agricultural livelihoods become increasingly unstable due to water scarcity, it is anticipated that rural-urban migration will escalate, contributing to the ongoing urbanization trend in the region. The migration can also lead to increased informal settlements, particularly on flood-prone, high-risk land. The risks include sudden floods, outbreaks of infectious diseases, and spikes in food prices. (Serdeczny et al., 2017)

Water pollution

After accounting for accessibility, water quality can diminish the quantity of available clean water for domestic use. Moreover, a study by WHO projected that clean water could be overstated, particularly if the water sources were poorly maintained (Genesis, 2023). Nonetheless, the intended use of the water determines its acceptable quality. Thus, water that is unsuitable for domestic use may still be utilized for agricultural or industrial purposes, where clean water is not necessary. However, in some regions, the quality of water is declining sharply, making it unsuitable for any kind of application (Crisis Watch, n.d.). China presents a typical example with 54% of the Hai River basin so polluted that it is deemed unusable for any purpose (Wikipedia, 2023)

In Africa, including SSA contaminated water sources are a major problem that requires immediate action. Human activities such as agriculture, mining, and deforestation, coupled with crumbling infrastructure, poor governance, and the unchecked operations of foreign industries, all contribute significantly to water pollution (McClure, 2021). Stressful environments such as pH changes, hypoxia or anoxia, elevated temperatures, high turbidity, or salinity variations are other sources of water pollution (Wikipedia, 2023). Coolant water in industry and power stations is a common source of thermal pollution. Furthermore, the continent's excessive reliance on fertilizers and pesticides for agricultural production leads to water pollution as these substances frequently end up in water systems, compromising water quality (Bensen, 2022)

In Kenya, Tanzania, and Uganda, the livelihoods of hundreds of villages, depend on Lake Victoria, the world's largest tropical lake. However, the future of the lack is increasingly destroyed by water pollution from sources such as mining wastewater, raw sewage from lakeshore villages, pesticide and fertilizer runoff from adjacent farming activities (McClure, 2021). Ironically, some fishing practices also contribute to water contamination, worsening the environmental degradation of the lake (McClure, 2021). For Kenya, water pollution problems are made worse by recurrent floods and the impingement of large water towers, which reduce water infiltration while increasing surface runoff, siltation, soil erosion, and flash floods (Nkatha, 2024)

The destruction of Africa's priceless green lung regions, the Congo Basin and Cameroon presents a typical example of deforestation (McClure, 2021). When natural vegetation is removed, silt and other pollutants are washed into rivers, causing water pollution. Therefore, preserving and restoring forest ecosystems is crucial not only for maintaining water quality but also for ensuring water availability for communities and ecosystems dependent on these resources. The far-reaching repercussions of deforestation extend beyond the immediate borders. For example, extensive deforestation in central Africa is estimated to decrease rainfall in the US Midwest by as much as 35% (Nkatha, 2024). This could have profound effects on global food and water supplies. Thus, highlighting the interconnectedness of environmental changes across continents.

Overall, contaminated drinking water poses severe health risks, potentially causing water-borne diseases. UNICEF highlights fecal water pollution and elevated concentrations of arsenic and fluoride as major global water quality problems (Wikipedia, 2023). In low-income countries, approximately 71% of illnesses are linked to inadequate water and sanitation conditions (Wikipedia, 2023). Globally, polluted water contributes to an alarming statistic of 4 000 deaths per day from diarrhea in children under the age of 5 (UNICEF, 2024).

Progress made in addressing water scarcity in SSA

The goal of water security is to maximize the benefits of clean water for people, animals and the environment, while minimizing the risks of harmful impacts, such as floods to an acceptable degree. Thus, addressing water scarcity problems in SSA demands a comprehensive strategy, encompassing sustainable, long-term solutions to secure reliable water sources for vulnerable communities. Various organizations, including the UN, WHO, UNESCO, World Bank, World Vision, and other non-governmental organizations (NGOs) have spearheaded different WASH programs aimed at boosting the availability of fresh water, reducing its demand and facilitating its reuse and recycling to address the water crisis in water-stressed communities. For example, World Vision has worked closely with relevant government institutions and other stakeholders to create sustainable WASH programs in some of the worst water-stressed countries in the world, including SSA (Bensen, 2022). Table 1 shows some progress made for the ten worst-affected countries in SSA.

Table 1: *Water access in the worst water-stressed SSA countries* (Reid, 2023)

Country	PLACW (%)	World Vision supported water provision progress (2019)
Niger	54	Household sanitation provision to 98,000 people Clean drinking water access to ~ 100,000 people
DRC	54	Construction and renovation of 468 new water stations and wells Clean water provision to over 125,000 people. Cholera outbreak containment and quarantine assistance to schools, health centres, and families during Ebola crisis
Chad	54	Four boreholes were constructed to service various communities, Clean water provision to 29 000 people 34 communities achieved certification as open defecation-free.
Ethiopia	50	Enabled communal clean water provision to 350 000 people 396 000 people constructed toilets in their households 450 000 people educated on good sanitation and personal hygiene
Somalia	44	Facilitated clean water access to 350,000 people Constructed boreholes and rehabilitated shallow wells Built three innovative rainwater-harvesting dams.
South Sudan	59	Clean water provision to 195,480 people in the Upper Nile Consistent daily supply of clean water to 125 000 internally displaced people and their host communities Facilitated clean water access to 5797 pupils in 8 schools Taught good hygiene practices to 292,042 and 70% now wash their hands, particularly before meals 42,076 persons have better health because of the built latrines
Uganda	44	Assisted 350,000 people with clean water access in their homes Water stations were installed in nine schools,
Angola	43	Increased clean water access from 0% to 59% in 16 communities Introduced boreholes, tap water, and restored water stations. Constructed water sources near homes, affording, women and girls time for school and household chores
Mozambique	37	Facilitated the provision of potable water to over 87,000 people Assisted almost 74,000 in establishing home sanitation.

PLACW-people lacking access to clean water

From Table 1, significant progress has been made in providing clean and safe water to the worst affected countries. However, more work still needs to be done to ensure 100% achievement of the SDG 6 targets. The success of SDG6 necessitates the establishment of water facilities capable of supplying adequate water for domestic, industrial, agricultural, and service sectors, while also ensuring comprehensive wastewater management across these sectors (Ighobor, 2023). This is crucial since the attainment of all the other SDGs, particularly SDGs 1(no poverty), 2(zero hunger), and 3 (Good health and well-being) are directly linked to SDG6. According to the Global Water Security Assessment report, 2023, none of the SDGs can be accomplished without water security (Ighobor, 2023). Perhaps this explains why so many goals are being missed worldwide.

Based on the 2023 Water Security Assessment report, eighteen nations reduced the number of deaths linked to WASH between 2016 and 2019. These include Liberia, Ethiopia, Uganda

Ghana, and Zimbabwe which declared WASH commitments (Ighobor, 2023). On the brighter side, countries like Angola, Botswana, Gabon, DRC, and the Republic of Congo, are demonstrating effective water management practices, despite many countries scoring poorly on water use efficiency (Ighobor, 2023). Improved clean water availability and sanitary facilities were afforded to 569,000 people in SSA by the Water Project Inc (Wikipedia, 2023). This was achieved through adequate funding which enabled the completion of more than 2500 projects and 1500 water points. The Water Project Inc. is a nonprofit agency dedicated to implementing sustainable water projects across SSA, including Rwanda, Uganda, Kenya, Sudan, and Sierra Leone. The project initiatives emphasize educating communities on good sanitation and hygiene habits while also boosting water infrastructure through boreholes, well structure upgrades, and implementation of rainwater harvesting techniques.

Healing Waters International (HWI) supplies custom-designed water purification systems to water-stressed communities in Africa and around the globe (Lai, 2022). The organization has implemented numerous water purification initiatives across SSA, delivering safe and clean water to areas facing water stress. Examples include: (i) Eight sustainable water purification systems situated in or near urban areas in Rwanda, owned and managed by residents since 2013. These systems offer clean water, jobs, and sustainable income to area residents (ii) Clean water programs across Uganda, many utilizing solar power to ensure operational reliability in locations with unreliable electricity supply since 2013 (iii) A water purification system in Embakasi, Kenya, providing safe water and employment opportunities to the local community since 2015 (iv) Six essential water purification systems in Somalia, aimed at reducing waterborne diseases since 2013, (v) A water filtration system in Sierra Leone benefiting both the local community and a health clinic serving 7,000 people annually since 2013. The water purification systems may also include Home-based water treatments, such as sodium dichloroisocyanurate (NaDCC), Solar disinfection (SODIS), chlorine, and boiling water, which are part of the United Nations' SDG 6 Goals (Nkatha, 2024). The purification systems meet immediate needs for clean, safe water while establishing sustainable sources for the future. However, some challenges, such as inadequate maintenance, insufficient education, or a lack of equipment spare parts, may suppress the efficacy of at-home treatment options.

In collaboration with FAO, the Malawian government launched a "mega farm" initiative and rehabilitated 34 irrigation schemes countrywide. Additionally, the UN agency has expanded financial support to 127,000 smallholder farmers in rural Malawi to embrace climate-smart technologies. However, all these efforts are hampered by widespread malpractice and corruption. For example, the Affordable Inputs Program (AIP), originally introduced as the Farm Inputs Subsidy Program (FISP) in 2004, aimed to boost agricultural productivity and assist low-income households in Malawi was rigged with corruption and failed to meet its objectives. Moreover, the AIP costs generally exceeded the benefits, which the anti-poverty charity ActionAid attributed to the continuous budget shortfalls at the Ministry of Agriculture in Malawi (Kaliza, 2023).

The WHO states that a system of Water Safety Plans (WSPs), can be established to guarantee a consistent supply of safe drinking water (Bensen, 2022). WSPs assess the quality of water supplies to make sure they are fit for human use. The International Water Association (IWA) and the WHO drafted the WSP Manual in 2009, which provides guidelines to water utilities in the development of WSPs. The manual details how to evaluate water systems, create monitoring protocols, periodically review the WSP, and make assessments in the event of an incident.

Strategies and perspectives for addressing water insecurity in SSA

Water scarcity does not always result in a water crisis. This has been demonstrated in Israel, a nation with over 50% desert terrain and chronic water scarcity. The country has steadily reduced the overuse of freshwater by implementing widespread recycling of wastewater (> 90%) and desalination of seawater, alongside good governance, regulatory measures, effective innovation, and pricing strategies (SAZF, 2023). As such, Israel is acknowledged as a global leader in water technology and management. Other examples include Singapore and Las Vegas, Nevada, where the water crisis has been averted using similar strategies to Israel, as well as removing water-thirsty grass (Reid, 2023). Valuable lessons could be drawn from Israel and implemented to mitigate water crises in SSA. Additionally, governments and water managers must implement regulations that promote sustainable water governance and conservation, establish and enforce clear water-use policies for industries, businesses, and residences, and commit to infrastructure upgrades and maintenance to reduce water loss. Future-focused planning involving a wide array of mitigation strategies that encompass different types of storage, surface water, groundwater, green water, and potentially unconventional water sources is crucial (Ighobor, 2023). Research and innovation focussing on water-efficient, sustainable farming methods should be supported. Simple actions like collecting rainwater, planting water-efficient crops, and irrigating with grey water using drip or spray irrigation techniques instead of inundation of fields, are examples of more water-efficient agricultural practices.

Apart from increasing financial resources allocated to water quality, robust initiatives emphasizing pollution reduction should be promoted. For example, policies, subsidies, or levies aimed at enforcing industrial wastewater pre-treatment, and lowering agricultural runoff should be prioritized. Desalination in coastal areas and the use of recycled wastewater in low-quality water applications should be encouraged. Land use planning, such as the placement of industrial facilities outside urban regions should be enacted. Water-efficient energy sources such as solar and wind should be embraced to prevent power outages brought on by water scarcity. Additionally, addressing irrigation needs must be a top policy priority and a key area for long-term investment across SSA. Only six SSA countries, including Mali, Kenya, and South Africa, have striving irrigation schemes (Kaliza, 2023). AGRA, an African-led initiative aimed at achieving agricultural self-sufficiency in Africa states that irrigation in Africa could potentially increase agricultural productivity by 50%.

On the other hand, green infrastructure and nature-based solutions are among the most important strategies to minimize water stress and enhance water management. Restoring and preserving wetlands, mangroves, and woodlands can reduce the cost of water treatment while simultaneously enhancing water quality and increasing resistance to floods and droughts (McClure, 2021). Thus, funding institutions, including international development banks, should explore strategic debt relief schemes, such as debt-for-nature swaps, or debt relief in exchange for investment in resilient infrastructure such as wetland conservation or mangrove restoration. Furthermore, governments must implement education initiatives to increase public awareness of water resource conservation. Communities and residents should actively participate in decisions and actions regarding the governance and management of water resources. Crucially, action must be taken on climate change and the industries responsible for pollution and biodiversity loss. These propositions may seem impractical, but every country may avoid a water crisis by implementing effective management practices.

Conclusion

The problems with water insecurity in SSA will not go away unless drastic reforms are made. Addressing both physical and economic water scarcity is crucial, and this can only be accomplished through government political will, adequate funding, and collaboration with professionals across various sectors. Strategic investment in innovative technologies and resilient infrastructure to withstand severe weather conditions is important. Effective policies for sustainable water management, including stronger watershed management practices are needed. Promoting sustainable agricultural methods and water conservation education will empower local communities and improve resilience. Additionally, investing in early warning systems and disaster preparedness is crucial to reducing the impact of natural disasters like floods on water quality and public health in SSA. By prioritizing these initiatives, a way could be forged for a more water-secure future in SSA and Africa as a whole.

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THE APPLICATION OF ZN-MOF-5 FOR SELECTIVE METHANE CAPTURE PRODUCED FROM LANDFILLS: SYNTHESIS AND CHARACTERIZATION

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ABSTRACT

Methane is a greenhouse gas that has been demonstrated to be more harmful than carbon dioxide (CO_2) in terms of contributing to global warming, particularly in the first 20 years after its release into the atmosphere and consequently causing global warming. Metal-organic frameworks (MOFs) geometrical and topological properties are significant in influencing their capacity to selectively capture and store methane (CH_4). Landfill methane capture and storage by adsorption technique using MOFs as adsorbents has demonstrated some effective and efficient trends in reducing methane emissions from the environment by offering a vast surface area, favourable steric interactions, thermal stability, and hydrophobic pockets.

The aim of this study is to synthesize and optimize zinc metal-organic framework (Zn-MOF-5) under various conditions of temperature ranging from (85°C to 100°C), as well as reaction time from 24 hours to 48 hours and test its suitability to selectively capture landfill methane through comprehensively exploring physicochemical properties including the functional groups, crystallinity and thermal stability using Fourier Transform Infrared (FTIR), X-ray Diffraction (XRD) and Thermogravimetric Analysis (TGA). The FTIR findings on Zn-MOF-5 reveal that the material possesses two broad bands C-H stretching vibrations at 2980 and 2871 cm^{-1}, C=O stretching vibrations at 1658 cm^{-1} peak linked to Zn^{2+}, respectively

Keywords: Global warming, Greenhouse gases, Metal organic framework, Methane emissions and capture, Physicochemical properties.

INTRODUCTION

Climate change, driven mostly by human activity, has emerged as one of the most important global concerns. Rising global temperatures, widespread changes in weather patterns, and previously unheard-of environmental effects have resulted from the increase in atmospheric concentrations of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which has also significantly altered the Earth's radioactive balance (Bhatti et al., 2024).

The Intergovernmental Panel on Climate Change (IPCC) has firmly underlined the importance of anthropogenic GHG emissions in driving climate change, recognizing the urgent need for thorough study to understand the complex interactions between climate change and GHG emissions (Chang et al., 2022). Wide-ranging and complex, the effects of climate change include changes to ecosystems, an increase in sea level, harsh weather, and problems with agriculture and water supplies (Chang et al., 2022).

Methane (CH_4), the second most significant greenhouse gas after carbon dioxide, is released into the atmosphere by a range of sources at varying amounts (the global average mean atmospheric methane abundance peaked in 2022 at 1,911.88 parts per million) (Wang et al., 2020a). However, methane is non-polar and interacts extremely weakly with most materials, unlike CO_2, which has a quadrupole moment and may be trapped both physically and chemically in a variety of solvents and porous solids. Methane capture is therefore a problem that can only be solved thorough material screening and creative molecular-level designs (Wang et al., 2020a).

Landfills are the third-largest source of anthropogenic methane (CH_4) emissions. According to the United States Environmental Protection Agency (EPA), methane emissions from municipal solid waste (MSW) landfills in 2021 were equivalent to the greenhouse gas (GHG) emissions from nearly 23.1 million gasoline-powered passenger vehicles driven for one year or CO_2 emissions from nearly 13.1 million homes' energy use for one year (EPA, 2023). When compared to CO_2, CH_4 is a powerful greenhouse gas that has a 25-fold greater potential for global warming. In addition to being a greenhouse gas, landfill gas (LFG) collecting systems have the potential to be utilized as a clean fuel source for power generation or heat delivery (Bian et al., 2019).

Metal-organic frameworks (MOFs) are a new type of crystalline porous material made up of organic ligands such as carboxylic acid linkers, nitrogen-donating ligands, and heteroaromatic linkers that form a coordination connection with a metallic node (Bhuyan et.al., 2024).

MOFs have been studied in the following domains: separation, catalysis, chemical compound detection, and drug delivery, with a focus on adsorptive processes (Xiang et al., 2020). The selectivity of these materials is determined by a number of factors, including the size pore and the amount of synergy, which allows for the formation of regular and selective cavities and the chemical stability of structures, as well as the physical or chemical interactions between metallic ions and pairs of electrons free from bonding functional groups (Menezes et al., 2023).

Metal organic frameworks consist of macro and micro-porous materials, inorganic components (clusters) interact with organic components (ligands) to generate three-dimensional crystalline structures (Peng et al., 2023). The metal ion and the organic ligand can interact using hydrogen bonding, covalent interactions, π-π stacking in aromatic compounds, and other mechanisms Nadar, 2019). The metal ions, cobalt, aluminum, titanium, copper, zinc, and zirconium are the most often utilized ones since they interfere in the process of crystallization to improve the crystallites of MOF. The most used organic ligands are tetrazolates, triazolates, imidazolates, pyrazolates, terephthalic and trimesic acids, since they provide superior thermal and chemical stability compared to those manufactured and based on carboxylates (Nadar et al., 2019).

The employment of appropriate adsorbents with high selectivity and adsorption capacity is necessary to remove CH_4 from the landfill. In this experiment, MOF-5 was used. Zinc-based metal-organic frameworks (MOFs) are thought to be the best for adsorption because of their wide accessible pore volume, variable pore size, and high specific surface area. Given its strong gas selectivity and capacity, MOF-5 is regarded as one of the MOFs materials that has been studied the most (Wang et al., 2020b).

In particular, Zn-MOFs samples are often used as adsorbents in the CH_4 adsorption processes. Zn-MOF-5 is a metal organic framework compound which consists of a Zinc (Zn) metal and terephthalic acid ligand, which is also known as IRMOF-1 with a cubic structure. The Zn-MOF-5 is notable for its porous nature, high surface area to volume ratio which is approximately 2200 m^2/cm^3, and it has been used in gas storage due to its large pore size (Jiao et al., 2019).

Therefore, this study is focused on synthesizing Zn-MOF-5 using the solvothermal technique and study its physicochemical properties to evaluate its potential suitability for to capture CH_4 released from landfills. The aim is to produce Zn-MOF-5 crystals through the solvothermal process, which have a high capability of adsorbing CH_4 at room temperature and excellent thermal stability.

RELATED STUDIES

Wang (2020) conducted an experiment to explore the effect of reaction duration, temperature, and the molar ratio of zinc ion to terephthalic acid on the formation of the crystal MOF-5. The parallel flow drop solvothermal method was used to synthesize the crystal of MOF-5 with a metal ion to organic ligand molar ratio of 2:1 at 140°C, a reaction time of 12 hours, a drop acceleration of zinc nitrate of 50 mL/min, a drop acceleration of terephthalic acid of 40 mL/min, and a drying temperature of 110°C. The FTIR analysis results depicted that the terephthalic acid is totally protonated, and the Zn^{2+} and carboxyl groups are generated by the coordination of the multi-tooth bridge in the MOF-5 crystal. The thermal stability of MOF-5 crystals generated by the molar ratio of metal ions to the ligands and the reaction temperature were optimized, indicating that the thermal stability increased as the molar ratio of metal ions to the ligands increased. The current study relates to this research project since it focuses on optimizing the molar ratio, reaction time and temperature to explore any effect to the synthesized Zn-MOF-5 results.

According to Li et al., (2018), recent improvements were highlighted in gas storage and separation utilizing metal-organic frameworks (MOFs). MOFs were used as adsorbents or membrane materials in CO_2 extraction. Efforts in MOF-based adsorbents are mostly focused on improving the CO_2 or O_2 affinity of MOFs. As a result, selectivity's in post-combustion capture (CO_2/N_2), direct capture from air (CO_2/N_2), and oxy-fuel combustion (O_2/N_2) were strengthened. Notably, several alkylamine-modified CO_2-selective MOFs had extraordinarily high CO_2 working capacities with strong recyclability at the requisite capture circumstances. Room-temperature methane storage with MOFs, on the other hand, is considerably closer to being accomplished. Some reported MOFs' total methane uptakes have exceeded the DOE objectives. Future work might concentrate on Future research on more practical issues such as the kinetics of CH_4 adsorption/desorption in MOF-filled tanks, the packing efficiency of MOF particles, and how to reduce the cost and enhance the reusability of MOFs (Li, 2018).

An experimental study was conducted by Mohammed (2021) in-which MOF-5 was hydrothermally synthesized with Zn_4O inorganic vertices. A three-step activation procedure consisting of drying in an evacuated environment, exchanging solvents, and preserving in the original solvent was carried out, and it was discovered that activation is effective because it increases the samples' ability for methane adsorption.

METHODOLOGY

Material synthesis

The crystalline Zn-MOF-5 was synthesized using the solvothermal method by adding zinc nitrate hexahydrate, terephthalic acid and Diethyl formamide (DEF) as the zinc source, organic ligand, and solvent. The crystal MOF-5 was synthesized by adding 2.496 g zinc nitrate hexahydrate and 0.528 g terephthalic acid. Dissolved in 60 mL DEF under 300 rpm constant agitation at ambient conditions and degassed three times using a freeze pump thaw and put into an oven to allow for different reaction temperatures 85, 88, 90 and 100 °C, as well as different reaction times 24, 36, and 48 hours.

After the given reaction time and temperature elapsed the solution was removed from the oven. The golden crystals which had formed on the walls and bottom of the vials and were separated from the solution through decantation process, washed with DEF three times to remove the unreacted zinc-nitrate hexahydrate; thereafter, purified with chloroform by adding it to the vials containing the raw Zn-MOF-5 crystals. The vials containing Zn-MOF-5 crystals and chloroform were then placed back to the oven at 70°C for 3 days. Samples were replenished with chloroform every day for 3 days and the crystals turned from golden colour to translucent, stored in chloroform since Zn-MOF-5 is susceptible to air.

Material characterisation

Both the XRD and the FTIR analyses were conducted at the Tshwane University of Technology – Department of Chemistry. The TGA analyses was conducted at the University of South Africa.

The XRD Bruker D8 advance was utilized to run the samples at an angle range of 2 theta = 5-90 degrees. The XRD was utilized to determine the crystalline material of the Zn-MOF-5 phase which yielded data on unit cell size. The material under analysis was homogenized, finely powdered, and its average bulk composition was ascertained.

The FT-IR PerkinElmer UATR Two Spectrometer was utilized to run the samples at ambient temperature. Fourier transformed infrared spectroscopy (FTIR) was used to determine the characteristics of the Zn-MOF-5 functional groups. For this study, the spectra of the Zinc-MOF-5 samples were achieved by using an attenuated total reflection (ATR) spectroscopy in transmission mode. The samples were analyzed at ambient temperature. All spectra were achieved at resolution of 8 cm^{-1} and a collection of scans per spectrum, in the frequency range of 4000 – 400 cm^{-1}.

The TGA analyses was utilized to determine the thermal stability, of the samples. During TGA analysis, a sample was heated while being passed through an environment of inert gas while being continuously weighed. Gaseous by-products were produced during reactions involving several solids. These gaseous by-products were eliminated–by TGA, and variations in the sample's residual mass were noted (Luis et.al., 2020).

RESULTS AND DISCUSSION

Surface chemistry (FTIR)

The FTIR spectra of the synthesized Zn-MOF-5 depicts two broad bands at 2980 and 2871 cm^{-1} which are attributed to the C-H stretching vibrations of the methylene/alkane's groups in DEF molecules, confirming the removal of guest molecules from the structure. The peak that appears at wavelength 1658 cm^{-1} is attributable to the asymmetric stretching vibration of the C=O group linked to Zn, while its symmetric stretching vibration emerged at 1383 cm^{-1}. The band at 644 cm^{-1} is ascribed to the symmetric stretching vibration of Zn_4O. The band at 3605 cm^{-1} is related to the presence of water with the metal coordination. It is therefore crucial to have these bonds as they will assist with opening the pores for the methane capture during the methane capture and storage (Wang, 2017). The FTIR spectra of the Zn-MOF-5 crystals in Figure 3 and 4 displayed that the reaction time and reaction temperature optimization does not significantly change the crystalline structure of the material and does not affect the properties of the Zn-MOF-5 compounds.

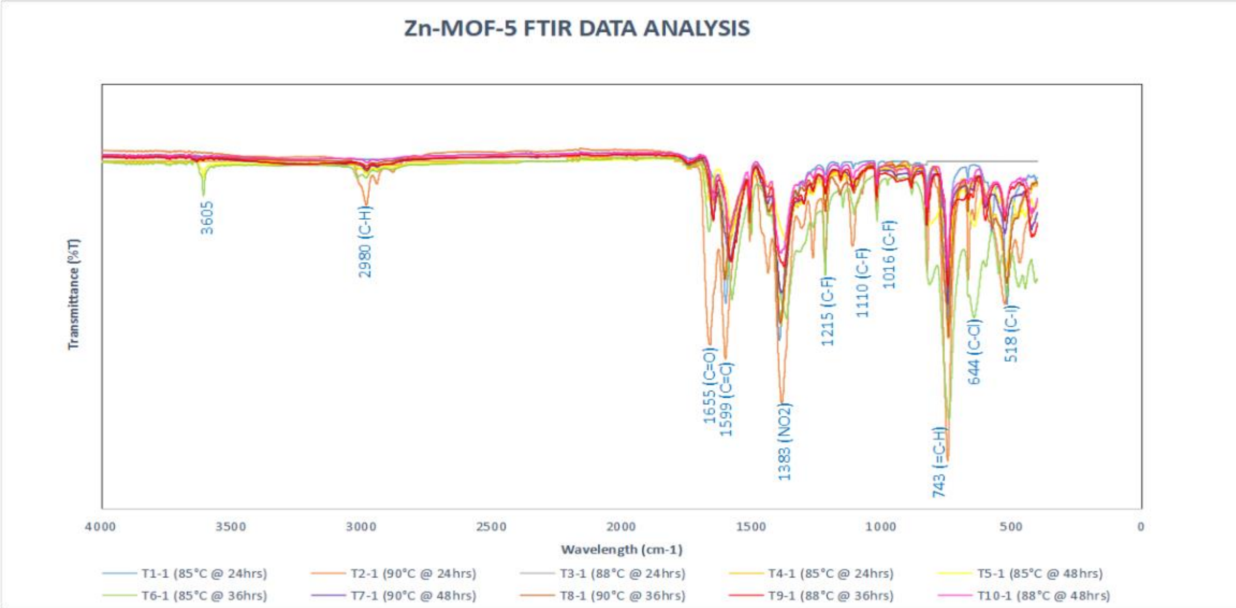

Figure 3: *FTIR spectrum of the synthesized Zn-MOF-5 at 85, 88 and 90°C for 24, 36 and 48 hours.*

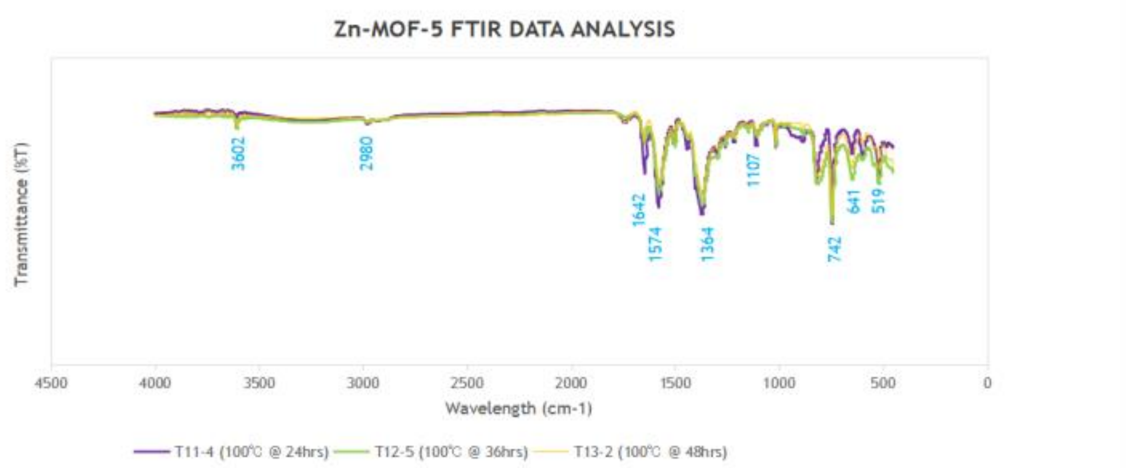

Figure 4: *FTIR spectrum of the synthesized Zn-MOF-5 for 100 °C at 24, 36 and 48 hours.*

Crystallinity (XRD)

The XRD patterns of the synthesized Zn-MOF-5 at various temperatures and reaction times are shown in Figure 5. The patterns of the Zn-MOF-5 trials exhibit its two typical peaks at the range of 8.03° to 9.07° (2θ) and 10.71° to 11.06° (2θ). These broad peaks indicate an increasing regularity of crystalline structure and better alignment layers. No broad changes have occurred by the various reaction times and temperatures. X-ray diffraction (XRD) patterns are used to determine the crystal structure of materials. In the context of methane capture, XRD patterns may be utilized to examine structural changes in the material throughout the adsorption process.

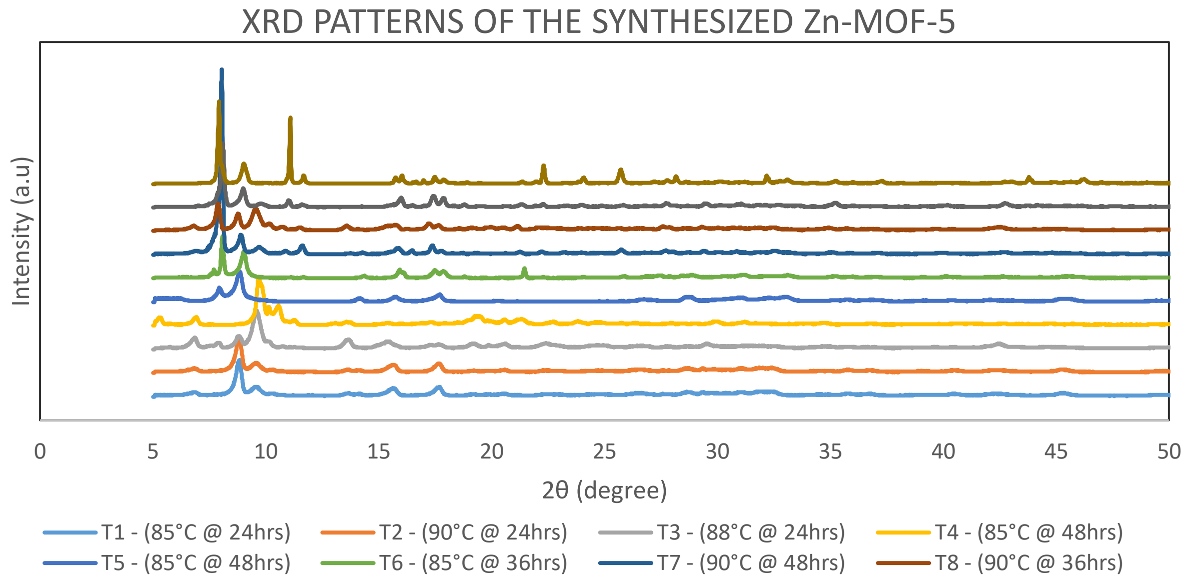

Figure 5: *XRD patterns of the synthesized Zn-MOF-5 at 85, 88 and 90 °C for 24, 36 and 48 hours*

Thermal properties (TGA)

Figure 6 shows the thermogram of the synthesized Zn-MOF-5 samples. The TGA temperature was chosen based on TGA results. As shown in Figure 5, the weight loss of Zn-MOF-5 during the heating from room temperature to 800 °C could be divided into four main stages: (1) the first stage (weight loss: ~1%) as located below ~80 °C could be ascribed to the removal of water adsorbed on the surface of the material; (2) the second stage (weight loss: ~9%) between ~ (100–130) °C was mainly due to the dissipation of the residual solvent molecules (DEF) incorporated in the frameworks; (3) significant weight loss (~40%) occurred around ~ (400–540) °C of the third stage, which should be caused by the thermal decomposition of the Zn-MOF-5 skeleton. During this stage, carboxylic bridges between benzene rings and Zn_4O clusters broke, releasing CO_2 and benzene, and Zn-MOF-5 crystals were pyrolyzed into a composite of ZnO and carbon; (4) as the temperature continued to reach around 600 °C, carbonaceous materials started to deoxidize ZnO to Zn with itself being oxidized mainly into CO_2 and CO; when reaching the boiling point of the zinc metal monomer (908 °C), the gaseous zinc would begin to evaporate under the nitrogen current flow. This reaction was the most intense at 950 °C, and the weight loss of this stage was ~28%. Therefore, the temperature zone to tune the ZnO morphology was selected between (500–600) °C, where carbon was produced from the decomposition of organic components but little consumption of carbon to reduce ZnO.

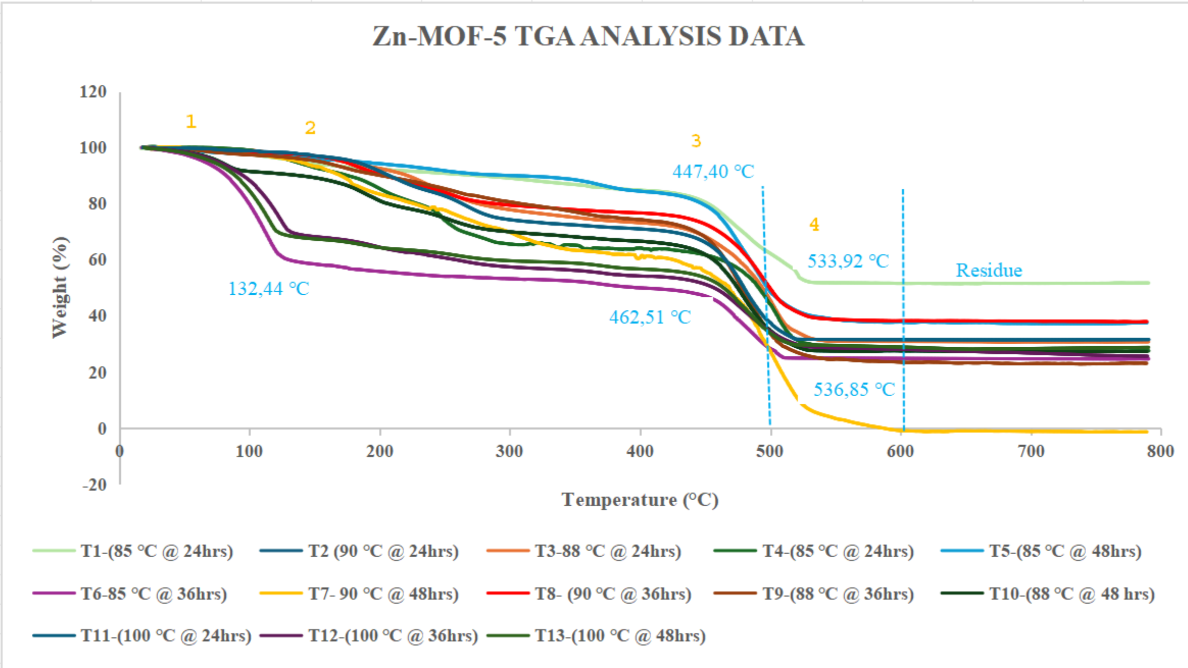

Figure 6: *Thermogram of the synthesized Zn-MOF-5 at 85, 88, 90 and 100 °C for 24, 36 and 48 hours.*

CONCLUSION

The MOF-5 was synthesized using solvothermal technique by employing diethyl formamide solvent and this MOF structure was obtained from the Zn (BDC) system where BDC=1,4-benzodicarboxylate by DEF as a solvent. Zinc nitrate, terephthalic acid and DEF were applied as the zinc source, organic ligand, and organic solvent, respectively, in the study. The Zn-MOF-5 samples were characterized using XRD and FTIR and the results were in relation to literature due to the presence of the functional groups which proves that the obtained porous carbon was protonated without special surface functional groups.

FTIR results obtained broad bands which are attributed to the C-H stretching vibrations of the methylene/alkane's groups in DEF molecule and asymmetric stretching vibration of the C=O group linked to Zn. XRD obtained broad peaks which indicated an increasing regularity of crystalline structure and better alignment layers. The thermogram weight loss in two stages observed during the thermal analysis (Figure 5) can be attributed to the evaporation of the non-volatile absorbed species like DEF (Diethyl formamide) during the first stage and decomposition of the framework structure during the second stage. All the samples showed overall thermal stability up to 462 °C. Comparing TGA results showed that the thermal stability which occurred on each stage for the were similar with the previously done work on Zn-MOF-5 by Wang, et.al. 2023, this proves that the Zn-MOF-5 was synthesized accurately.

CHALLENGES AND FUTURE WORK

MOFs are being invented for storing gases and separation, with notable advances in this area. They have a distinct advantage over other porous materials because of their adjustable interior surface chemistry via organic and inorganic functionalization. MOFs have far higher porosity and modularity than typical porous adsorbents such as zeolites and activated carbons, making them suitable for a high level of gas storage. This, together with advancements in metal-ligand combinations, may result in multivariate MOFs, highlighting the need of pore and topological engineering in the future. Their record absorption capabilities for H_2, CH_4, and C_2H_2 are exceptional. This study focuses on CH4 capture using MOF-5, future work can focus on C_2H_2 and H_2 capture since their record adsorption capabilities are exceptional.

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THE CONTRIBUTION OF INDIGENOUS WATER TREATMENT TECHNIQUES IN RURAL DEVELOPMENT IN SUDAN

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ABSTRACT

This study delves into the invaluable contributions of indigenous knowledge and techniques in water treatment throughout the various stages of water treatment collection, harvesting, storage, and management in rural Sudan. The research evaluates methods such as filtration, coagulation, and other pertinent techniques for treating water that may be contaminated due to traditional harvesting practices during the rainy seasons. Furthermore, the investigation highlights the pivotal role of diverse tribal and ethnic communities in managing and ensuring the responsible use of shared water resources. While government efforts tend to prioritize infrastructure development for improving the quality of life, access to clean water remains a paramount concern.

In this context, the study adopted the ethnographic technique as a pivoted method by applying an online survey (n=56) and direct interviews, and it emphasized the need for greater recognition of indigenous knowledge, culture, heritage, and belief systems that have evolved over centuries, allowing communities to navigate challenging periods of water abundance and drought. Notably, some indigenous practices involve using plant roots, such as the coagulation technique, specifically focusing on using moringa seeds. Additionally, water quality is enhanced through filtration and adsorption processes, effectively reducing biological contaminants, cations, and anions. Various technologies can achieve this, including sand filters, pottery clays, and other coating materials. 80% of participants still use plant parties as safe materials for the water treatment process; sand filters, alum, and ceramic pots are also used.

The study concludes that indigenous water treatment techniques offer a viable solution for water management, particularly in rural areas of Sudan that are distanced from central government services. In summary, the combination of indigenous knowledge and appropriate technology has the potential to safeguard public health and ensure sustainable water resources management.

Keywords:*Traditional water treatment, indigenous knowledge, appropriate technology*

Introduction

In 2017, the United Nations presented a report on its resolution 70/1 on transforming the world for 2030 Sustainable Development Goals (SDGs). The report focuses on access to safe drinking water, sanitation, and the benefits of ecosystems to human health and environmental sustainability. In 2015, over 90% of the world's population used improved drinking water facilities, and two-thirds used improved sanitation facilities. However, many rural areas still lack suitable water resources and suffer from poor sanitation facilities. The new direction for managing water and sanitation is to look for contributions from stakeholders and the participation of local communities to address these sectors. A survey conducted between 2016 and 2017 found that over 80% of 74 responding countries had a plan for sharing service users and communities in water management. In 1992, the United Nations launched the International Year of the World's Indigenous People. The declaration focused on strengthening international cooperation to address the problems indigenous communities face in human rights, the environment, development, education, and health.(Weiland et al., 2021).

Indigenous knowledge is used as a basis for decision-making in developing countries regarding food security, human and animal health, education, water harvesting and purification management, and other activities. This practice is explicitly applied in rural areas far from the central government. Indigenous knowledge can improve the view of the twenty-first-century project due to its tendency to focus on the relationship between human beings and their ecosystem, while modern science attempts to persuade institutions and people to adopt green practices. African social institutions have maintained respect for the ecosystem (Branch, 2011), (Weiland et al., 2021).

In Sudan, most communities, especially in eastern and western regions, rely on water harvesting methods for various needs such as agriculture and domestic use due to uneven population distribution and water resources. Randel (1961) pioneered research on traditional water harvesting in Sudan. Rainwater runoff management is crucial for enhancing food production during drought seasons. The Teras technique, notably used in areas receiving 100 to 400 mm of rain annually, involves constructing dams or bunds to capture water from floods, particularly in eastern, central, and western Sudan. In Kassala, Teras covers 6 to 10 feddans, combined with wadis for cultivation and water storage (Ahmed & Mohamed, 1994).

Residents in Kordufan and Darfur use Baobab (*Adansonia digitata L*), locally known as Tabaldi in Kordufan and Kuka in Nigeria. It belongs to the Malvacaea family. It can be found in most of sub-Saharan Africa's semi-arid and sub-humid areas. Its multi-purpose fruit is considered a tree of life due to its numerous uses, such as food and medicine, and contains the best fibers, Adigiatat, which has been used to make ropes, cordage, nets, snares, finishing lines, mats, and cloth. The secret to employing Baobab for water storage is that, because of its unique anatomical structure, the thickness diameter contains parenchymatous pith ranging from 1.3 to 1.5 mm, when the stem diameter is 5 mm (Eltahir, 2013) (Kotina et al., 2017).

Jahn and Dirar (1979) emphasize the importance of indigenous knowledge in water management sectors. In her major study, Jahn examined using some pants such as *Moronga*, *Maerua pseudopetalosa,* and *Hibiscus Sabdariffa*, which they applied as bio-coagents and disinfectants in water purification. (Jahn & Dirar, 1979). Some types of treatment are based on sense and sensibility. Some herbs, traditionally called [Marhabibe] or [Maheribe], have changed the water test. The scientific name is Juncus. High levels of iron and magnesium sulfate were recorded. On the other hand, the concentration of alga in hafier is responsible for the wrong test results in some regions in Darfur (interview with someone from Darfur). Besides flavors, Juncus is widely used in the system treatment wetlands (TWs). The constructed wetlands (CWs) have been used as a green technology for treating domestic, agricultural, industrial wastewater, and mine drainage, with other plants as chemical oxygen demand (COD) removal because the amount of dissolved and suspended organic carbon is primary pollutant of wastewater (Taylor et al., 2009).

This study set out the impact of indigenous technique contributions on the water management sector through nine states in Sudan.

Methods

Ethnographic methods focus on button-up participation as modernization approaches. The main resources of these methods are participant observation, interviews, and archival research. The current study adopted ethnographic research techniques familiar with indigenous knowledge (Whitehead, 2005).

An online survey questionnaire was conducted (n=56), as well as observation and analysis of related study findings, from November 2023 to January 2024 through nine states in Sudan. Observation methods and semi-structured interviews provide insight into the spatial and temporal context of indigenous knowledge for sustainable water management. Participants were chosen to produce a nominally stratified sample based on rural social status.

The participants were surveyed for the following information: location, family numbers, occupation, education level, dwelling house, water resources, access to water, the color and the odor of the water, groundwater, methods of treatment for turbid water, the perfection of water quality, and water-related diseases. The results of the study were analyzed the following theme:

- Contribution of Indigenous Water Treatment Techniques in rural development in Sudan
- Indicator for access to safe water in rural areas
- Indigenous technique tools for water treatment
- Limitation and change of indigenous practice.

Survey outline:

About 26.3% of responses were from Khartoum; other states, such as Aljazeera, White Nile, Red Sea, Algadarf, North states, and North Kordufan states, recorded weak responses. And one response from all Darfur states. Because of the un-coverage of the internet network due to the ongoing conflict since Aprile 2023.

Most participants were educated up to high school except one person, subsistence farmers who owned between 5 to 60 hectares, while the majority, about (35%) were government employees, and the others were in the private sector.

Water Resources in Sudan: The main water sources in Sudan consist of surface water, such as rainfall, rivers, seasonal wadis, khors, lakes, and wetlands. Approximately 45.5% of 2010 groundwater was extensively utilized in three main basin aquifers: Nubian sandstone, Um Ruwaba, and Alluvial deposits. With annual recharge close to 1,563 BCM, alongside non-conventional resources like wastewater reuse and desalination (United Nations Environment Programme, 2020). Sudan encounters average yearly temperatures ranging from 26°C to 32°C, with summer temperatures in the northern areas frequently 43°C. Rainfall patterns in Sudan are inconsistent and unpredictable, exhibiting significant diversity between the northern and southern regions. While the north typically receives minimal rainfall (less than 50 mm annually), central areas receive between 200 mm and 700 mm yearly, and certain southern regions receive over 1,500 mm annually. Most of the rainfall transpires during the rainy season from March to October, with the highest precipitation levels occurring between June and September (Cairncross & Kinnear, 1991)

The native administration system in Sudan: The Native Administration (NA) in Sudan refers to the formal institution of traditional governance systems. This system is primarily used in rural areas, especially among nomadic or semi-nomadic communities. Originally adapted from pre-existing practices by British administrators during the Anglo-Egyptian Sudan colonial period, it has persisted since independence. The NA system grants formal powers to traditional leaders, complementing their informal influence within their communities. These leaders manage and conserve the environment, resolve land and natural resources conflicts, and sometimes wield significant economic power1. Despite criticisms dating back to the colonial era, the NA system plays a crucial role in effective administration, particularly in rural regions and among nomadic populations. It is a vital link between these communities and external entities, including aid organizations. The system operates through three tiers of governance: paramount chiefs (nazir), who preside over Omdas (mayors), who preside over sheiks. These leaders may hold various titles, such as nazir, sultan, melik, prince, or shartai1. The NA system combines formal authority with historical indigenous heritage, uniquely shaping Sudanese governance. Besides administration duties, NA has been adhering to local customs and traditions, managing and organizing nomadic movements, conserving the environment, and mediating conflicts between nomads and farmers (Elhussein, 1989), (Ismail et al., 2021).

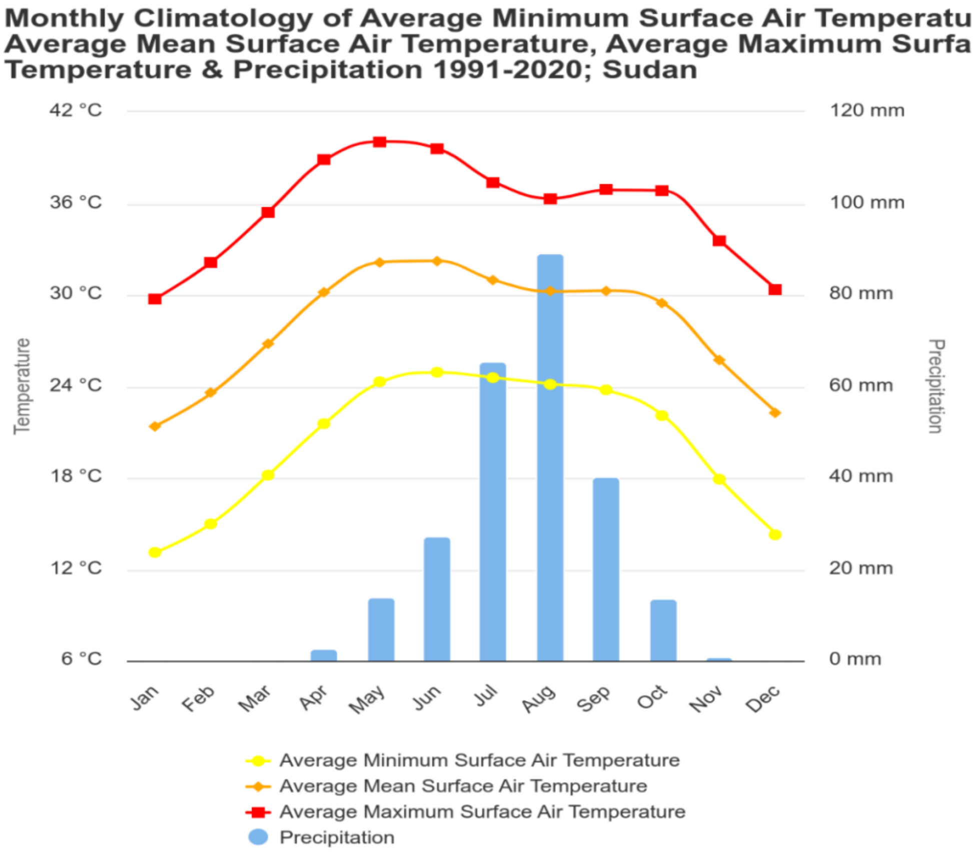

Figure 1: Monthly rain falls from 1991-2020 (World Bank)

Results and discussion

Water resources: In Sudan, water is used for agriculture, drinking, and other purposes—most rural households engage in agriculture, either crop farming or raising livestock. For most participants (66%), their central resource is groundwater, while 7.14% still use hafer for drinking. Only 13% of respondents use Wadis, canals, and the Nile River for farming. According to UNICEF, about 68% of the households in Sudan have access to essential improved water resources. Approximately 32% of the population drinks unsafe water from unimproved sources. Most of these water sources are surface water, with others being groundwater (open wells and damaged groundwater aquifers) (UNICEF, 2017). From the survey results, 74.4% of respondents do not suffer from water odor because they have good renewable resources, such as the Nile River with a high rate of turbidity, while 13.9% suffer from the salty odor and 11.6% from unpalatable odor. Fig 2 presents the results obtained from the survey. As the literature describes, groundwater has weak turbidity and may have high salt concentration due to the rock-base and its dynamic due to the interaction between water and rock-base. (Yasin & Adam, 2016), (Arifullah et al., 2022)

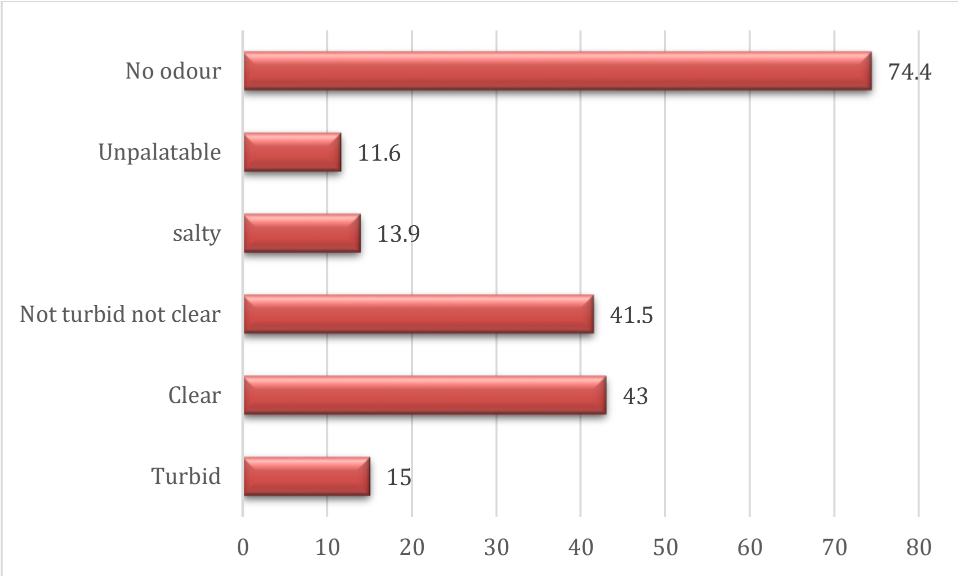

Figure 2: Physical properties of the drinking water

Water treatment techniques: Results in Fig (2) revealed that (80%) of participants preferred to use plants as safe water treatment techniques for reducing water turbidity, especially in autumn. They applied the plant's roots, leaves, and stems. Only (30%) still use alum as percipient agents for turbid water, while others use ceramic pots (15%), sand filters (25%), and regular precipitation and boiling water. Throughout history, Sudanese people have used many practical methods to reduce the contaminants in the water. The first coagulant agent is applied by adopting plant seed powder of three types or more. A powder seed of the moringa (*Oleifera Lam*) family (*Moringaaceae),* Sudanese people prefer to call it [Shgara Rouaq], which means [Clarifier tree]. It grows in many parts of the Sudan. The technique is straightforward: the plant seeds were dried and crushed in a mortar [Fonedg] to obtain fine powder, then directly added to the turbid water. Sometimes, a stirrer for 10 to 30 min will be necessary. However, another coagulant agent, the woody herb *Maerua pseudopetalosa,* whose local name is (Kordala) exists in the Blue Nile, Southern and Western parts of Sudan and was examined to reduce the turbidity and suspended solids. In addition, natural clays were applied to remove turbidity in the East Nile bank in Wad Elsied. Table 2 summarizes the central processing in the water treatment sector in Sudan (Jahn, 1979; Jahn & Dirar, 1979). (Jahn, 1977)

Table 1: Water Resources

Groundwater	Scarface water (Hafer)	Storage in trees	Surface water (wadis, canals, and Nile River)	Wadis	Others (public tap)
66%	7.14%	12%	8.9%	5.35%	5.35%

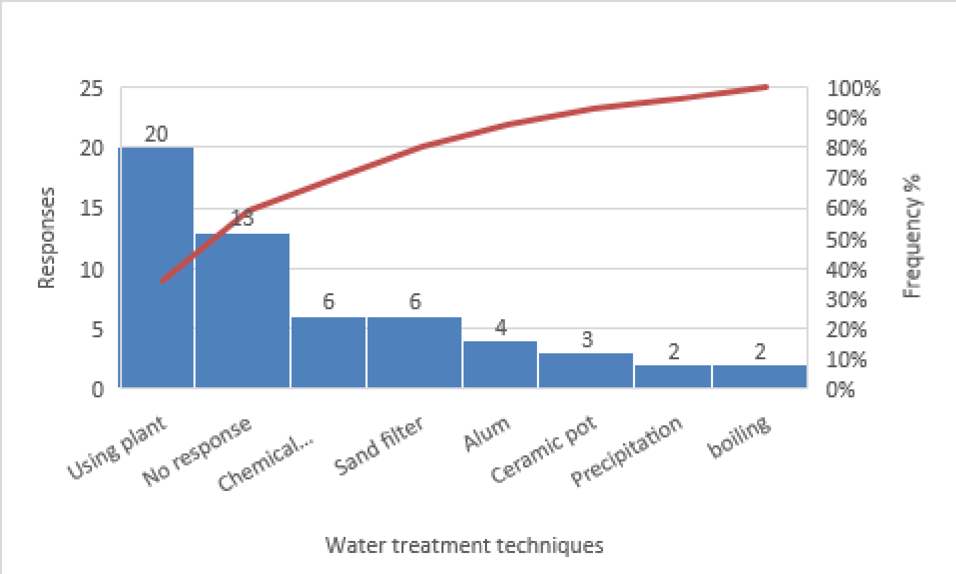

Figure 3: water treatment practices

Table 2: Plants Used in Water Treatment

Scientific name	Family	Local name	Local use	Average dosage of powder used. (teaspoon/kg)
Moringa	Moringaaceae	Shgara Rouaq	Medical uses	3
Maerua Pseudopetalosa	Capparidaceae	Kordala	Eaten and medical uses	3
Red sorrela	Malvacea	Kerked	Uses as juice	3
Boscia senegalensis	Capparaceae	Mukheit	Eaten and medical uses	-
Ocimum basilicum L.	Lamiaceae	Rehan	Flavor fresh and food	-
Adansonia digitata L	Malvacaea	Tabeldi	Storage water and medical uses	-
Juncus spp.	Juncaceae	Maheribe	Medical uses and flavor	-

Practices of Indigenous techniques

Participants were surveyed for three main factors limiting indigenous techniques: their effectiveness, sustainability, and knowledge transfer through the generations. Less than a third of those who responded (28%) are satisfied with indigenous techniques. They believe this technique is active, can be transferred through generations, and is sustainable because it is natural and made from friendly materials 23, 28, and 22 %, respectively. Figure 3 shows an analysis of the Indigenous process. In 2014, Mahlangu reported a new and convenient synthetic procedure to study the factors limiting of using Indigenous methods in water management in Khambashe, Eastern Cape South Africa, to indicate sufficient documentation, un-enthusiasm of the community members, effective practices, time factor, and the restriction of transfer knowledge. Based on his survey, the majority of village members strongly agree that indigenous knowledge is out of date practice due to flounces of Western culture (Mahlangu & Garutsa, 2014)

The innovative and seminal work of Ghorbani et al. pioneered a new approach to investigate the interaction between community social structure, indigenous knowledge, water management technologies and practices, and water governance norms in the context of anthropogenic climate change using qualitative methods. The authors suggest that combining hierarchical land ownership-based water distribution with 'bilateral compensatory mutual assistance' for low-profit agricultural water users results in a model of standard pool resource management that improves community drought resilience (Ghorbani et al., 2021)

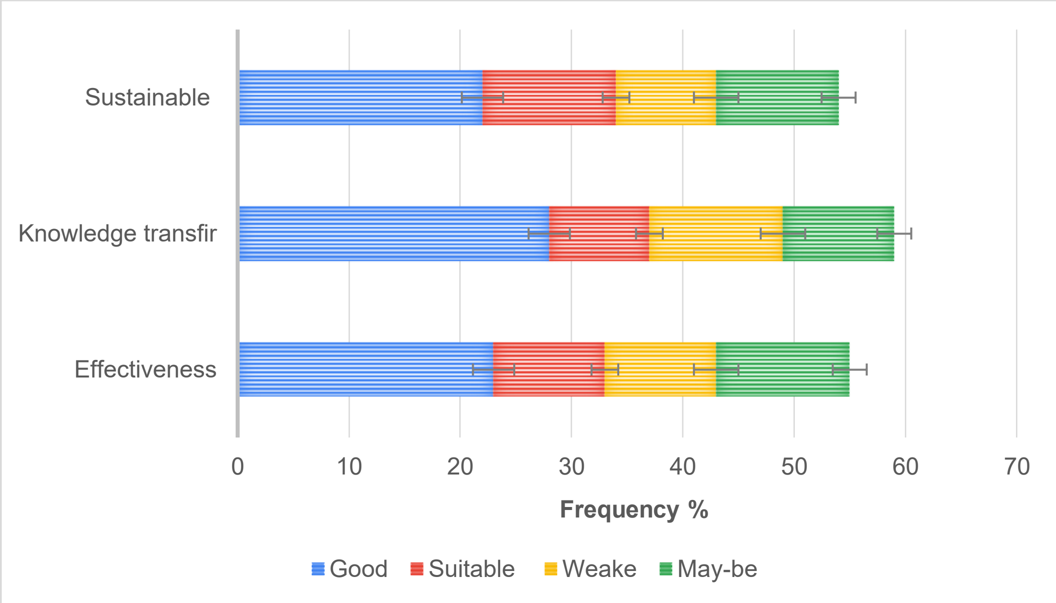

Figure 4: Analysis of Indigenous process

Conclusion

In conclusion, the research has shed light on the significant role of Indigenous process techniques in water treatment and management within rural Sudanese communities. Through a comprehensive approach involving surveys, interviews, and literature analysis, it has been revealed that traditional methods remain prevalent among the populace for harvesting and treating drinking water. Utilizing plant-based remedies to reduce turbidity and eliminate impurities from surface water exemplifies the resourcefulness and sustainability inherent in Indigenous knowledge systems. These findings contribute to the existing body of literature and underscore the importance of recognizing and integrating Indigenous practices into contemporary water management strategies. It is imperative to explore and leverage Indigenous knowledge further to address water-related challenges, ensuring the well-being and resilience of rural communities in Sudan and beyond.

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SECTION: SUSTAINABILITY

Edited by Diran Soumonni and John Trimble

USING ANIMAL DATA TO MONITOR ANIMAL HEALTH USING MACHINE

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ABSTRACT

Monitoring livestock in the traditional way is very challenging for Herders who have to inspect and observe animals in the field directly. The drawbacks of this method are that Herders are not aware when can the livestock get sick, as it is difficult to perform check-ups due to the constant state of roaming needed for livestock activities. This situation calls for time-consuming efforts when done traditionally. And as the location of the animals is a major factor in livestock control, Herders facing animal theft issues also need to use livestock location tracking. Other problems that face this method is that clinical techniques for monitoring animal health are not adequate because they provide scattered information and need supervision through an appointed veterinarian. By which, any health care system configurations will not be effective in cases that require immediate treatment. New technologies such as sensors, machine learning, and the Internet of Things (IoT) offer a new possibility for Herders that look for easier access to vital information that help in early and proper decision-making. Becoming straightforward or proactive by using the monitoring services provides an opportunity to monitor key animal health parameters continuously, which will help us in achieving greater efficiencies and gains in animal husbandry. It enables Herders and physicians to stay updated on livestock health levels and they can also detect various diseases early. In this paper, we will make an intelligent animal health monitoring system to solve problems related to animal health monitoring. We will use animal sensor data to predict animal activities using a machine learning model that uses two algorithms: SVM and Ensemble classifier. The system will monitor animals' activities, and predict six different livestock activities, which will open new possibilities for improving animal monitoring methods. This will reduce the cost, time, and effort required for monitoring and providing the required services.

Keywords: Machine learning, Monitoring Systems, Prediction, SVM, Ensemble Classifier

INTRODUCTION

Background:

Livestock in general, are domesticated animals such as cattle raised in an agricultural environment suitable for the production of milk, fur, leather, eggs, meat, and wool, and this concept is called on animals that are raised inside farms such as cows and goats.

In the past decades, the traditional pattern of animal husbandry prevailed , which is the open grazing system. Given In many countries rich in livestock, especially third world countries, the traditional method of breeding in covering the internal and external demand for animal products today is noticed to have low productivity caused by low husbandry rates, which in return are expressed in weak economic return.

Because animals cannot communicate verbally with humans, their illness is detected through their bodily behavior. Any change in this habit could be an early sign of a medical condition. It also conveys the herd's social interactions. The animal's owner notices the change and takes the animal to the nearest hospital, veterinarian, or drugstore for an examination. The doctor notes the changes in behavior depending on the animal owner's complaint, and these behavioral changes provide a crucial indication by recognizing probable ailments and other diseases. The trouble with this old system is that it's tough to keep track of, count, and control livestock numbers. Clinical procedures for animal health monitoring are insufficient since they provide dispersed information and do not explain the animal's health status all at once. This healthcare system fails to manage emergency circumstances, and you must wait for a veterinarian to diagnose the problem, which takes a long time. Herders must also be aware of the whereabouts of their cattle in order to track them. In livestock monitoring, the position of grazing animals is crucial. When animals must separate from the herd due to disease or heat, tracking them is useful.

The situation in the country where you are located has an immediate impact on livestock. Many countries are grappling with a slew of issues relating to animal health and the delivery of essential services. The difficulties include the difficulty of preventing diseases and limiting their spread or transmission to humans, the difficulty of veterinary services reaching livestock, which are primarily found in rural areas of most countries, and the ineffectiveness of the traditional monitoring method, which relies on manual examination and visual observation. Another issue is the emergence of wars and tribal conflicts in many countries, which occur as a result of some tribes stealing the livestock of other tribes. Location tracking systems can be used to address this issue. In addition, in nations with broad territories, it is difficult for ministries in charge of livestock to oversee and count cattle, making supplying them with the necessary services and private medical treatment a challenging effort. The lack of a consistent and strong system for collecting and analyzing data is contributing to the Ministry of Livestock's poor performance. All of these factors conspired to make providing services challenging.

The lack of basic needs and deterioration of services in the field of livestock care In almost every country have been significant. Sudan, for example, is regarded one of the richest Arab and African countries in terms of cattle, with it accounting for roughly 30% of the Arab world's livestock value. Sudan's animals are raised in a traditional manner, and it's agricultural sector has contributed only 5% of the country's GDP over the last 30 years. The cattle sector, which is the Sudanese's true oil, has failed to fulfil its potential as a source of foreign currency. Because of the lack of a standardized mechanism for data collecting, it is difficult to provide medical services, as well amidst wars and disputes caused by livestock theft. (Wilson, 2018)(Ajak & Demiryurek, 2021)(Leff, 2009)

In this research, we will create an intelligent animal health monitoring system, and use animal sensor data to forecast animal activities using machine learning. To solve difficulties linked to animal health monitoring, the created system can accurately anticipate six activities: running, jogging, walking, standing, eating, and sleeping. This brings up new avenues for enhancing animal monitoring techniques. As a result, the cost, time, and effort required to monitor and provide the required services will be reduced. This paper is composed of five chapters. Chapter two will display some related works. Chapter three will talk about the system design which will explain the proposed solution. Chapter four will discuss the results obtained by testing the system. And finally, in Chapter five, we will talk about the conclusions and recommendations for further improvements in the system.

RELATED STUDIES:

It has been elaborated by authors of similar works, who classified five dairy cow activities, that multiple binary classifiers were trained independently for each activity with an ensemble method. A subset of features that performed best for each activity was selected using embedded feature selection. Both studies fixed the orientation of the sensor on the cows.(Kamminga et al., 2018)

An ear-borne accelerometer in extensively grazed sheep was used in (García et al., 2020) for behavioural classification using machine learning algorithms. The following four ML algorithms were assessed through three epochs (5, 10, and 30 seconds), on the following 19 derived-movement features: Classification and Regression Trees (CART), SVM, Linear Discriminant Analysis (LDA), and Quadratic Discriminant Analysis (QDA). Three different echograms were used to evaluate behaviour classification, including grazing, lying, standing, and walking; active behaviour and inactivity; and body posture. Using a 10 seconds epoch, SVM (76.9%) was the most accurate method of detecting the four mutually exclusive behaviours (grazing, lying, standing, and walking), whilst CART (98.1%) was the most accurate method. It was found that LDA, using 30 seconds epoch, was superior in detecting posture (90.6%).

Based on an acquisition of depth images via the Kinect v2 sensor and a software program that identifies the posture of sows, they developed in (García et al., 2020) a detection system. On the 15th day of postpartum, five frames per second were obtained for a testing data set on a sow, and different sows were collected for training data sets. Zheng et al. demonstrated that the automatic detection from depth images can successfully avoid disturbances of the light caused by in-situ heat lamps and day-night cycles that impact the identification performance of RGB images. Compared to standing (0.4% at night and 10.5% during the daytime), and sitting (0.5% at night and 3.4% during the daytime), Zheng et al. (2018) found that the sow spent the majority of her time recumbent (92.9% at night and 84.1% during the daytime). Zheng et al. reports statistically that sows have an inconsistent activity level throughout the entire day, and their preferred lying positions are dictated by the pen's floor design.

The author of another paper collected mandibular motion data from a dairy cow by using a three-axis acceleration sensor and classified the cow's behaviours into three categories: eating, rumination, and other behaviours. The accuracy of eating recognition was 92.8%, and the accuracy of rumination recognition was 93.7%, by using the K-nearest neighbour algorithm.(Qiao et al., 2021)

Using 30 GPS measurements of dairy cows at pasture, in (García et al., 2020) they examined variable segmentation. In classifying grazing, resting, and walking, 13 ML algorithms (base learners) were tested using default parameters in the Waikato Environment for Knowledge Analysis (WEKA). Using the WEKA implementations, they then derived two stacking ensembles. First, the ensemble of the best performers. Using a manual ensemble selection method, a second ensemble was derived which was optimized for performance. An independent trial set derived from 10 cows was used to evaluate both ensemble versions. The ensembles were a success when using base learners based on boosting algorithms: Logistic model trees (LMT), Logistic Learning Predicate Trees (LLP), Naive Bayes (NB), Dynamic

Trees (DT), Naive Bayes tree (NBTree), Logistic model trees (LMT) and Sequential minimal optimization (SMO).

METHODOIOGY:

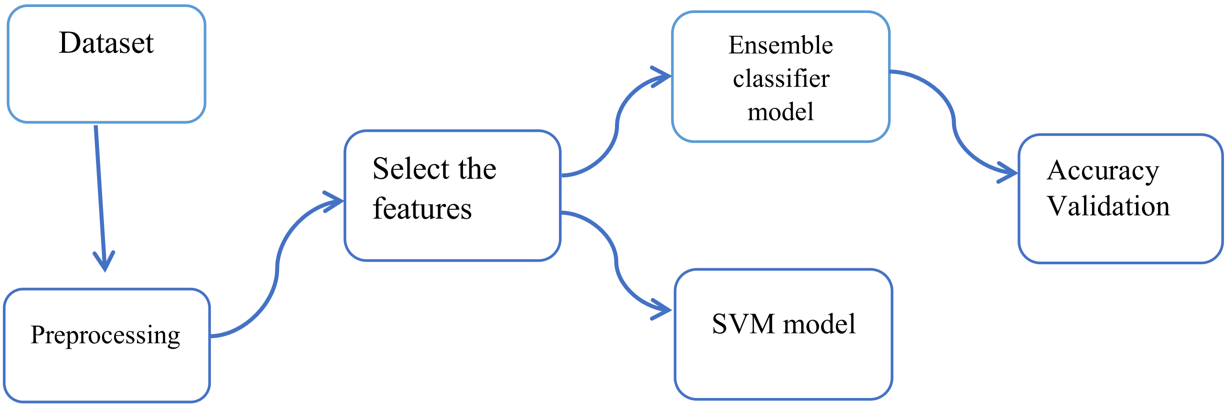

Figure 1: General System block diagram

Dataset:

In this paper, we used a related dataset from EASY website (easy.dans.knaw.nl). Data was collected by recording the activities of five goats on two farms in the Netherlands in a medium-sized area with different heights and simple terrain, and varied areas that allow for states of running, walking, sleeping, trotting, and jumping. The dataset is classified into two categories: a training data, and testing data. The data was divided into five volumes, each into five categories for each goat from G1 to G5 in a file. It was noticed that the first three goats were more inclined to rest and stand, and the last two were balanced in all activities, meaning that their data points are better for research. Data was collected from six sensor nodes that were fixed in different directions on a collar around the goat's neck. The sensors measure six activities, namely running, jogging, walking, standing, eating, and sleeping. All the data was taken from Goat 5 and we applied it in the work of the machine learning model because it is more balanced and unbiased in all activities if compared to the first three of G1-G3.

Pre-processing:

In pre-processing stage, we cleaned the data before entering it into the model. The data contained many missing values and contained many features. We chose the most important features and ignored the rest. We deleted some features because most of the data in them contained missing or very repetitive data.

Ensemble classifier:

we used Ensemble algorithm because it helps to improve machine learning results by combining several models. This approach allows the production of better predictive performance compared to a single model. The basic idea is to learn a set of classifiers and to allow them to vote on the best results and features.

Support Vector Machine:

Support Vector Machine (SVM) is a supervised machine learning algorithm that is commonly used for classification and regression challenges. Common applications of the SVM algorithm are: Intrusion Detection System, Protein Structure Prediction, Detecting Steganography in Digital Images, etc. In the SVM algorithm, each point is represented as a data item within the n-dimensional space where the value of each feature is the value of a specific coordinate.

Split data for training and testing:

We uploaded the data to Google Drive and the model worked on Google Colaboratory. The data was divided into 70%/30% split for training for testing, respectively. We chose 14 features from the existing features in the dataset to ensure the best results, then randomized it after that and selected the algorithm for the model. Finally, we trained the model.

RESULTS AND DISCUSSIONS:

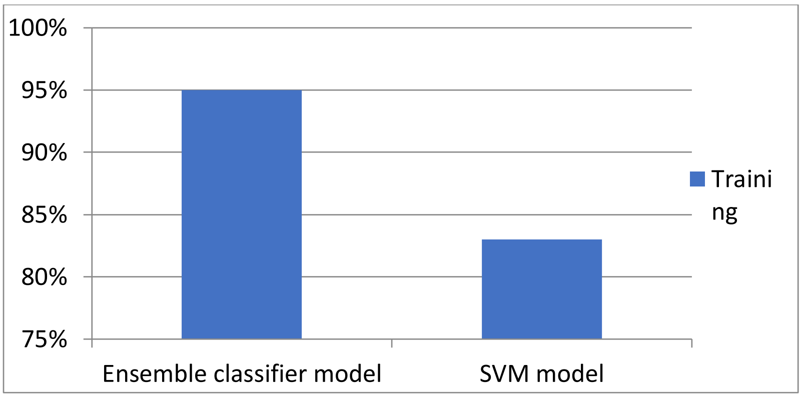

Fig.2. Distribution of data training accuracy

The main objective of our proposed framework is to use animal sensor data to predict animal activities using an appropriate machine learning model. We made a machine learning model using Google Colaboratory platform and TensorFlow 2.0, and used Python to write the code. We first conducted training and testing using the Ensemble classifier and used the fourteen most important features and ignored the rest. We got an accuracy of 95% in the training phase and 91% in the validation. Then we used SVM algorithm accordingly and got an accuracy of 83% in the training phase and 80% in the validation.

Finally, after making a comparison between the two models we found that although the algorithms used in each model are different, a higher accuracy was obtained using an Ensemble classifier algorithm compared to SVM.

Conclusion:

Since animals do not communicate with us directly, their diseases are recognized by their behavior; Any change in their behavior can be an early indicator of a specific disease condition. These changes provide an important signal by which to identify suspected diseases and other ailments. The problem with traditional animal husbandry is that clinical techniques for monitoring animal health are insufficient because they provide sparse information, and this health care system is ineffective in treating emergencies that require immediate treatment. In this paper, we proposed an intelligent monitoring system to track animal activities, which opens new possibilities for improving animal monitoring methods. This paper provides a framework for predicting animal behavior from data collected from sensors that monitor six activities: running, jogging, walking, standing, eating, and sleeping. Using the SVM and Ensemble classifier algorithms, we implemented machine learning models to obtain high prediction accuracy. The results showed that the Ensemble classifier has outperformed the SVM algorithm and was more accurate compared to the other model.

Future work:

In future research, we want to use Internet of Things (IoT) technology instead of embedded systems to collect the data, and give more attention to processing automation in the intelligent care process such as the detection of viral and bacterial diseases, adding animal location tracking, pulse, and heart rate sensors, use of thermal processing cameras rather than temperature sensors, and use of image processing to get to know the behavior of the livestock and its movements more accurately, to provide better identification.

Adding medical laboratory tests in the system database can be crucial as the system is a large and integrated database that contains all the data related to animals to facilitate the user's access to all the data needed everywhere at anytime. This process will be extended to Herders by designing an application that is easy-to-use with three different control interfaces to supply for the Herders and the doctor and the Ministry of livestock, as it will provide them with the necessary information, direct connectivity to facilitate access to the system at all times and places.

In future research, we will traying to apply such a system to Sudan as a country that is considered one of the richest Arab and African countries with its livestock. With the major problems it faces in controlling and monitoring animals and providing health and necessary services due to its vast lands and richness in livestock, the system will be a great alternative to replace the traditional methods used in the meantime.

This system can also be applied to the other countries with large areas and rich in livestock and have problems with health care and the provision of basic services.

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MAPPING THE CREATIVE ECOSYSTEM OF THE URBAN ARTISAN COMPLEX, VICTORIA YARDS

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ABSTRACT
Victoria Yards is a successful example of regeneration within the city of Johannesburg, South Africa. While the urban complex consists predominantly of artisan studios, it also focuses on educational facilities, urban farming and skills development, which contribute to the collective function of the creative enterprise. Throughout the effective growth of Victoria Yards, emphasis has been placed on the integration with surrounding communities and extending generated growth into adjacent suburbs. Creative industries offer a holistic view of the connection that cultural knowledge and technology have with industry and development, offering employment opportunities and socio-economic growth. Through the use of a case study methodology, this paper aims to map the creative ecosystem of the urban artisan complex of Victoria Yards to identify functional contributors and creative collaborations that enabled the successful development of the enterprise. Initially, the paper explores existing literature on creative ecosystems, outlining the value and drive that creative work contributes to contemporary economies. Based on a comprehensive understanding of theoretical approaches to mapping ecosystems, the study uses a combination of quantitative and qualitative methods to guide the mapping of the Victoria Yards creative ecosystem. The outcome of the study forms a precedent for sustainable and appropriate urban regeneration by outlining how the elements within a creative ecosystem can effectively interact with each other to generate sustainable social development and business growth resulting in human wellbeing and reduced inequalities, aligning with the principles of appropriate technology.

Keywords: Creative Ecosystems, Urban Regeneration, Creative Industries, Sustainable Development, Community Integration

Introduction

South Africa is often characterised as one of the most unequal nations in the world, experiencing extreme socio-economic disparities rooted in its apartheid past (Baker, 2019; Hurlbut, 2018). Due to the need for holistic approaches to sustainable development, this paper delves into appropriate technology and its role in urban renewal within South Africa's context. By acknowledging the substantial contribution creative industries offer to socio-economic growth, the urban artisan complex of Victoria Yards serves as a case study of how this approach can be successfully implemented. With this backdrop, the research question addressed in this paper is: How does the integration of appropriate technology and creative industries contribute to sustainable urban renewal in the context of South Africa?

By analysing existing ecosystem and creative ecosystem models, this paper reports on the mapping of the creative ecosystem of Victoria Yards. Located within a marginalized suburb in the city of Johannesburg, this case study serves as an example of sustainable urban renewal that follows appropriate technology principles. The study aims to illustrate how sustainable, and context-aware developments can lead to successful social and economic upliftment. Through the analysis of Victoria Yards as a creative ecosystem, this paper provides insights into its role in sustainable social development, business growth, and the reduction of inequalities and enhancement of human well-being.

Context: Urban Renewal in South Africa

South Africa has been described as one of the most unequal countries in the world (Baker, 2019; Hurlbut, 2018). This inequality was visibly depicted by TIME Magazine, which published a photograph of adjacent suburbs in Johannesburg (Figure 1); the affluence of Primrose directly bordering the informal settlement of Makause (Baker, 2019). Much of South Africa's inequalities are rooted in its apartheid past where racial segregation was dictated by an all-white government (Baker, 2019). Non-white South Africans, who made up the majority of the population, were forcibly relocated into townships on the peripheries of most cities (Baker, 2019). While many significant strides have been made in sustainable urban renewal since the end of apartheid in 1994, the effects of its institution are still felt today. Included in this aftermath is how the urban development during the apartheid area still affects how cities like Johannesburg are divided into affluent and impoverished areas.

Figure 1: *TIME Magazine, Primrose bordering Makause*

As a reaction to the neglect, inadequate planning, and ineffective leadership endured during apartheid, South African cities have engaged in large-scale renewal processes (Massey, 2020:266). However, urban renewal projects have often led to areas being gentrified (Massey, 2020:266). As poorer areas are renewed, more affluent businesses and residents are invited but previous inhabitants are resultingly displaced and ultimately already existing inequalities are amplified (Massey, 2020:266).

This illustrates a need for paying more attention to sustainable urban development within South Africa. The importance of sustainable development is reflected by the United Nations which has outlined 17 global Sustainable Development Goals (SDGs) as means of holistically and sustainably addressing social, economic and environmental evolution (United Nations, 2024). These objectives focus on reducing inequalities in developing nations, eliminating poverty and hunger, tackling climate change, ensuring access to education, and fostering inclusivity (United Nations, 2024). While the various goals are interlinked and address overlapping issues, goal 11 specifically addresses *sustainable cities and communities* directly (United Nations, 2024). This goal intends to "make cities and human settlements inclusive, safe, resilient and sustainable," (United Nations, 2024). The concept of appropriate technology offers insight into a holistic approach to the sustainable development of communities. While promoting the innovation for affordable, accessible and context-appropriate technologies, the approach also addresses the development of self-sustaining systems that consider local requirements (Patnaik & Tarei, 2022:3). As a result, appropriate technology intends to encourage development that supports the economic, political, social and cultural conditions within a context (Patnaik & Tarei, 2022:3). It is therefore evident that for urban renewal to be successful, the existing context must be taken into consideration, making sure that communities are integrated, and that the development is ultimately sustained by its local community.

While problematic urban renewal projects in South Africa do exist, others have taken a more comprehensive perspective. Victoria Yards, located in Lorentzville on the east side of Johannesburg's inner city, is a successful example of regeneration within an impoverished and marginalized suburban community. Victoria Yards is an urban artisan complex established in 2017 and is predominantly comprised of studios that are rented out to artists, designers, and crafters (Victoria Yards, 2024). Alongside this, it also focuses on educational facilities, urban farming and skills development, which contribute to the collective function of the creative enterprise (Victoria Yards, 2024). In the 1900, the complex was built as an industrial laundromat before evolving into an informal yard for mechanics (Mini, 2024). During the renewal process, emphasis was placed on keeping the aesthetic of the original buildings which were repaired instead of demolished and rebuilt as seen in Figure 2 (Mini, 2024). Since its inception, the enterprise has prioritised its integration into the surrounding community in order to avoid gentrification and contribute to the sustainable upliftment and development of the area (Mini, 2024). Following the evident need for such appropriate developments within South Africa, Victoria Yards serves as an example of how a creative enterprise can cohesively operate.

***Figure 2**: Victoria Yards*

Creative industries have been viewed as significant contributors to the economic and social development of South Africa (DTIC, 2022). Defined as a sector in the economy that makes use of individual skill, talent, and creativity, creative industries contribute to job creation, social inclusion and sustainable urban development (Cunningham, 2002:54; Galloway & Dunlop, 2007:19; Jeffcutt, 2004:68). In essence, creative industries can be viewed as important role players in urban renewal (DTIC, 2022). As the economies of developing countries often rely on small to medium enterprises, it is important to consider how creative businesses in this field are supported (Patnaik & Tarei, 2022:1). Creative industries offer a holistic view of the connection that cultural knowledge and technology have with industry and development (Bakalli, 2015:21).

According to Jeffcutt, the creative process requires knowledge, networks and technology (2004:68). Creativity, and in turn creative industries, benefit from collaborative environments (Imanto, et al., 2019:345; Bednar & Danko, 2020:105). Imanto et al. advise that SMEs can increase their innovation capabilities by engaging with community networks, universities and the government (2019:345). This way, clusters and networks can be defined as effective tools for improving competitiveness and growth (Bakalli, 2015:22).

Victoria Yards generates a clustered environment for small and medium creative enterprises and is therefore a strong example of an environment that fosters creativity and innovation in a way that also supports sustainable urban development. It offers a valuable example of a holistic approach to appropriate technology.

Methodology

The study aims to map the creative ecosystem of the urban artisan complex of Victoria Yards to identify functional contributors and creative collaborations that enable the successful development of the enterprise. In order to achieve this aim, the study uses a case study methodology. A case study is a qualitative research methodology during which a phenomenon is investigated in depth within its context (Priya, 2021:94). During a case study, multiple methods of collecting data can be undertaken such as questionnaires, interviews, and document studies (Priya, 2021:95). Yin emphasises that it is necessary to have a clearly defined scope that frames the study and aids in the design of data collection (2009:18). This study was therefore undertaken in two phases. In the initial phase a literature review on creative ecosystems was conducted, reviewing existing methods for mapping creative ecosystems and establishing the design of data collection, while the case study data collection and analysis was undertaken in the second phase.

Within this study, the exploration of literature on ecosystems and creative ecosystems as well as methods used in their mapping was used to guide the mapping of Victoria Yards' creative ecosystem. The data collection methods during the case study included the review of grey literature on Victoria Yards, the geographical mapping of tenants in the complex, interviews with key actors, experiential knowledge and observations. The methods used are linked to creative ecosystem literature review and are described in more detail within the following section. Through the systematic analysis of this data, the creative ecosystem of Victoria Yards was mapped and outlines how the elements within a creative ecosystem can effectively interact with each other to generate sustainable social development and business growth. The outcome of the study intends to form a precedent for sustainable and appropriate urban regeneration in order to illustrate how appropriate technology and creative industries can aid in the growth of urban cities.

Creative Ecosystems

The Oxford Dictionary defines an ecosystem as "a biological system composed of all the organisms found in a particular physical environment, interacting with it and with each other. Also in extended use: a complex system resembling this," (Oxford English Dictionary, 2023). The term ecosystem gained traction in the mid-1900s as a useful description of the growth or decline of man-made systems (Tsujimoto, et al., 2018:50). Within this application, ecosystems do not have a clear definition, however, Tsujimoto et al. created an outline of original definition based on the review of 90 previous studies that engage with the ecosystem concept (Tsujimoto, et al., 2018: 49). They describe an ecosystem as an organic network of actors that each have "different attributes, decision-making principles, and purposes," (Tsujimoto, et al., 2018:49). The system can be analysed according to both its positive and negative aspects such as "ecosystem-level competition, predation, parasitism, and destruction," (Tsujimoto, et al., 2018:49). An ecosystem can be seen as functional when people establish patterns of behaviour that enable the flow of capital, ideas and talent within the system (Zamana, 2021:136; Dervisholli, 2019).

The mapping of an ecosystem can enable the understanding of the elements that contribute to its function or dysfunction. By outlining the actor-network, the ecosystem boundary, other contributing elements, and relationships within the ecosystem, the analysis, design, and management of the ecosystem is enabled (Tsujimoto, et al., 2018:55). Viewing an industry as an *ecosystem* allows for a "systemic and integrated analysis of production activities" (Kraak, 2017:3), highlighting the interdependence of contributing institutions.

While the concept of ecosystems has extensively been used in industries such as business, policy-making, and management (Tsujimoto, et al., 2018), its application within creative industries is more recent. Although definitions vary, *creative ecosystems* outline the value and drive that creative work contributes to contemporary economies (Jeffcutt, 2004:68). Alongside this, Mortati and Cruickshank have advocated for using creative ecosystems as a way of describing SMEs that engage in design to trigger "knowledge exchange mechanisms, creativity and innovation" (2011:1). The concept of a *creative ecosystem* helps describe how creative industries operate within an economy in a systemic and integrated way. More specifically, Harrington defines *creative ecosystems* as "the entire system from which creative activity emerges, including three basic elements, the centrally involved creative person(s), the creative project and the creative environment, as well as the functional relationships which connect them," (1999:323).

De Bernard et al. review existing theories and methods of *creative ecosystems* through an extensive literature review (2022). Their article includes an analysis of different methods and data types used when studying creative ecosystems. A quantitative approach is used in identifying the geographical location of creative industries to identify creative ecosystems locationally as done by Mengi, Bilandzic, Foth and Guaralda (2020) and Bednar and Danko (2018). Qualitative data has more commonly been used to study creative ecosystems, where participants have been interviewed to establish their awareness and perception of ecosystems (Gasparin & Quinn, 2021) or to outline dynamics and structures within creative activities and processes (Chung, 2016; Grabher, 2004). Qualitative methods are viewed as valuable as they allow for components and occurrences in a complex system to be identified (de Bernard, et al., 2022:343). A combination of locational mapping and qualitative investigation has also been used as an approach (Foster, 2020; Dovey, et al., 2016; Markusen, et al., 2011). Wilson and Gross (2017) advocate for a mixed-methods approach to allow for an inclusive and open research design.

As a result of varying definitions and data collection methods, creative ecosystem models also have multiple approaches. Through an analysis of multiple models, de Bernard and Comunian (2021) distinguished models through the absence or presence of hierarchy even if there is only one industry represented as central. Additionally, the models also indicate how and if connections between the visualised entities exist (de Bernard & Comunian, 2021). When reviewing creative ecosystem models, some are illustrated geographically (Mengi, et al., 2020,

p. 8; Foster, 2020:8), while others simply identify individual stakeholders (Neelands, et al., 2015). Further models illustrate the interconnected nature of an ecosystem (Foster, 2020:5; Dovey, et al., 2016:95; Gasparin & Quinn, 2021:9), while others are a combination of stakeholders and interconnections (Jeffcutt, 2004:77; Markusen, et al., 2011:9; Zamana, 2021:140). As mentioned by Bernard and Comunian (2021), some models also indicate a hierarchy or a centre of the ecosystem (Bakalli, 2015:45; Stern & Seifert, 2017).

Through the understanding of these approaches, the creative ecosystem of Victoria Yards was mapped by using a combination of qualitative and quantitative methods. What was included in the case study was defined quantitatively (Wilson & Gross, 2017). The precinct and its surrounding area were mapped using current geographical data from Google Maps. This provided a detailed outline of the physical space and its geographic context. Tenants were identified through a publicly available map that lists and locates all current occupants of Victoria Yards. This map served as a foundational tool for understanding the composition of the ecosystem. Thereafter the conditions that impact the ecosystem were described (Tsujimoto, et al., 2018:55), through the evaluation of grey literature on Victoria Yards and the surrounding suburbs. Additionally, experiential knowledge and observations as a current tenant of Victoria Yards informed an understanding of the utilities and infrastructure available within the precinct. The actor network (Tsujimoto, et al., 2018:55) was described to illustrate the interconnected nature of the creative ecosystem (Foster, 2020:5; Dovey, et al., 2016:95; Gasparin & Quinn, 2021:9) in order to showcase what makes Victoria Yards a successful form of urban renewal. This involved systematically analyzing the map of tenants and categorizing them based on their business outputs into four groups: artisans, social enterprises, urban farming, and entertainment businesses. The relationship between the actors was established through an interview with the precinct manager as well as a key occupant in each category. Alongside this, the Victoria Yards website was reviewed together with webpages of key actors, informing important motives and decision-making principles that each actor has and influence relationships within the ecosystem. By employing these methods, the study aimed to provide a comprehensive understanding of the factors that contribute to the success of Victoria Yards as a model for urban renewal. This holistic approach ensured that both quantitative data and qualitative insights were integrated to map the creative ecosystem effectively.

Results and Discussion

What was included in the case study was established geographically and included everything contained within the Victoria Yards (VY) precinct such as the businesses and enterprises that operate from VY, as well as the engagement of the surrounding community. The case study embodied a microcosm that reflects both the conditions within the suburb of Lorentzville and the thriving ecosystem within the precinct.

The environment of the ecosystem that impacts how it functions can be described by both the state of the suburb it is located in, as well as the circumstances within the precinct itself as both impacts how VY operates. Lorentzville is an impoverished and marginalized suburb, and its residents fall victim to a lack of education and employment opportunities. Nando’s, a renowned South African food franchise, chose to keep their original head office in this suburb and adjacent to VY, which initiated the revival of the surroundings. During the establishment of Victoria Yards, a commitment to sustainability was evident as the precinct was designed to function off the grid. Solar power and a borehole ensure that VY remains an attractive option for small businesses, mitigating the impact of rolling blackouts that South Africa is impacted by. The commitment to appropriate technology not only aligns with the principle of sustainable development but also provides a resilient infrastructure for businesses to operate from. All tenants are equipped with essential amenities such as a white-boxed studio, lights, water, sanitation facilities and secure parking. The provision of security and general maintenance further illustrates the commitment to creating an environment conducive to creative enterprises.

The actor network within VY was described in four categories, namely artisans, social enterprises, urban farming, and entertainment businesses and illustrate a diverse and dynamic community of tenants. Artisans make up the majority of the residents and include trades such as artists, printing studios, jewellers, seamstresses, photographers and carpenters. These tenants primarily function as small businesses and are economically driven, thus making up most of the income-generating body in VY by paying rent for space. These businesses also provide job opportunities to people in the surrounding communities, as many of them employ people who live in adjacent suburbs. This not only contributes to economic growth in the area but also leads to the direct social integration of residents in the surrounding suburbs into the ecosystem. The clustering of artisans from intentionally diverse creative fields was also found to minimise direct competition and encourages collaboration through client referrals and inter-business orders. This effect makes it evident that diversity and dynamic relationships within a creative ecosystem contribute to the overall health and well-being of the system.

The social enterprises within Victoria Yards are driven by a commitment to social integration. Examples of these enterprises are education centers for children and young adults that facilitate the teaching of school curriculums, computer literacy, and cultural extra murals. Alongside this, VY also has a social enterprise that focuses on food sovereignty and runs a feeding scheme while also facilitating waste reclaiming as a means to support sustainability and earning opportunities. These social enterprises illustrate how having socially driven motives enables a creative ecosystem to be accepted by its environment, creating a self-sustaining system as stipulated in the appropriate technology framework.

The Victoria Yards precinct also functions as an urban farm as the grounds in between studios were transformed into expanding gardens containing predominantly edible plants. The gardens are maintained by a team of community members, contributing to further local employment. Tours of the gardens are offered to visitors, which encourage exploration of VY in general and contribute to the amount of business that is brought to artisan tenants. These gardens are also used as an educational tool for children and young adults in the vicinity, serving as an example of ecological sustainability and food sovereignty. The grown food is sold to food vendors in Lorentzville who sell it on to people in the community, creating an income-generating source for small businesses outside of VY and further illustrating the ripple effect of economic benefits that the enterprise offers.

Victoria Yards is furthermore home to a handful of entertainment businesses, including a coffee shop, bar, and various food outlets. While these small enterprises cater to other tenants, they also attract visitors exploring the vicinity. Alongside this, VY also has a monthly open day during which additional market and food stalls are opened attracting both international and local visitors. These open days allow visitors to explore artisan studios, creating a deeper understanding of various crafts and the overarching narrative of Victoria Yards. This approach aligns with the principles of appropriate technology by promoting inclusivity and cultural exchange.

Victoria Yards, despite being impacted by the broader socio-economic and political climate of South Africa, represents a collective of resilience and sustainability. The success of the creative ecosystem that attracts both local and international attention, positions VY as a model for appropriate urban renewal. The real-world impact is evident and is illustrated in its inclusion in tourism routes and its prominent position on platforms such as Tripadvisor. Victoria Yards embodies the integration of appropriate technology, creative industries, and a holistic approach to urban renewal, serving as a precedent for sustainable and inclusive development.

Conclusion

Through the evaluation of socio-economic disparities within South Africa, the need for urban developments that contribute to sustainable, inclusive, and resilient cities is made evident. Appropriate technology offers a valuable framework for developing sustainable cities and communities. Recognising the significant role that creative industries play in social and economic development, the urban artisan complex Victoria Yards was identified as a suitable example of appropriate urban renewal. Employing a case study approach, the precinct was analysed by mapping it as a creative ecosystem and revealing the diverse and dynamic relationships that enable its sustainable growth and contribute to its surroundings. It is important to note that Victoria Yards benefits from both economic and socially driven motives, enabling its success. Aligned with the concept of appropriate technology, Victoria Yards serves as an example of a holistic and self-sustaining approach to urban renewal, contributing to innovation in creative industries, cultural exchanges, and economic growth within an urban context.

Based on the outcome of this study, future research could include conducting a comparative study between Victoria Yards and other urban artisan complexes. This could reveal different models of sustainable urban renewal and highlight best practices that can be adapted to various socio-economic contexts. Alongside this, it would be beneficial to study the relationship between creative industries and urban ecosystems in more depth. Such research should examine how creative clusters contribute to urban resilience, cultural exchange, and economic diversification in various urban contexts. These future studies will contribute to a deeper understanding of how urban artisan complexes like Victoria Yards can serve as models for sustainable and inclusive urban development, particularly in regions with significant socio-economic disparities.

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DESIGN FOR PLAY: THE DESIGN OF AN APPROPRIATE SENSORY-INTEGRATED PLAYGROUND FOR LOW-RESOURCE COMMUNITIES IN SOUTH AFRICA

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ABSTRACT

The UN Sustainable Development Goal 4, 'Quality Education', aims to achieve equitable education for all by 2030. Target 4.2 aims to ensure that all children have access to quality early childhood development (ECD) and pre-primary education in preparation for primary education. However, access to adequate ECD in South Africa is currently inequitable. The early years of life play a pivotal role in a person's lifelong development and well-being. Sensory integration refers to the brain's ability to process information received through the senses. Effective sensory integration during early childhood is critical, as it lays the foundation for cognitive development. Inadequate opportunities for holistic sensory integration can result in underdeveloped neural pathways leading to future academic, social, and emotional difficulties. Play serves as a platform for learning, growth, and development, and it plays a pivotal role in effective sensory integration. There is a scarcity of publicly available sensory-integrated play spaces or playgrounds in under-resourced communities in South Africa. This can be attributed to a lack of governmental funding and maintenance, as well as limited awareness regarding the importance of 'play' for ECD. Consequently, preschool children from under-resourced communities in South Africa face an increased risk of experiencing academic challenges. Improving sensory integration for preschool children in under-resourced communities could improve their cognitive development and scholarly performance and enhance their overall well-being. This paper presents findings from an Industrial Design BA Honours practice-based research project that explores how Design Thinking and Appropriate Technology Theory could inform the design of low-cost sensory-enriched ECD playgrounds for children in under-resourced communities. Employing a participatory, human-centred design approach, this project applied Design Thinking to develop a contextually appropriate innovative solution. The outcome Sensescape, is a low-cost, easy-to-assemble, adaptable playground design, crafted from locally available and recycled materials and standard components, enabling the system to be both locally produced and maintained.

Keywords: Sensory Integration; ECD; Appropriate Technology; Design Thinking; Human Centred Design

INTRODUCTION

We experience the world through our senses. Our ability to touch, smell, taste, hear, and see allows us to engage with and navigate the world around us. The two lesser-known senses, vestibular and proprioception, allow us to move, balance, and operate in space. Sensory processing or sensory integration describes the neurological process of receiving, organising, processing, and reacting to sensory stimuli making it possible to use the body effectively with the environment (Lestrud, 2013). Most importantly, our sensory systems form the foundation of our cognitive development.

Foundational learning starts long before formal education does. What and how we learn about ourselves, our bodies and our ability to move in our environments begins in early childhood.

The pre-school years of any child's life are a crucial time to lay down the foundations of development for participation in school on an academic, social, functional, and emotional level (van der Walt, 2021). This learning doesn't occur in a book, behind a screen, or in a classroom, but rather, through play. The ECD phase describes the stage of 3-6, before the commencement of formal schooling. At this age, many children attend playgroups, preschools, or daycare facilities. In the ECD phase, children grow, learn, and develop critical foundational neural pathways through sensory stimulation in a balanced regulated environment such as outdoor play spaces or community playgrounds. For children, the act of play exposes the child to a world of sensory stimuli and serves as the cornerstone for the overall well-being of children, influencing their physical, mental, intellectual, and social development (Sharif, 2014; Jaarsveld, Liebenberg, Rooyen & Rensburg, 2021). Experts therefore deem playgrounds important facilitators for children's social and cognitive development (Pellegrini, Davis, & Jones, 1995:846).

SDG target 4.2 aims to ensure that all children have access to quality ECD and pre-primary education in preparation for primary education. Currently, across many regions of South Africa, early childhood education for children under 5 years is described as "inequitable, inadequate, and inaccessible" (Visser *et al*., 2021). Sensory input is the basis for ECD (Centre on the Developing Child, 2007). Inadequate opportunities for sensory stimulation through play during this phase can lead to diminished cognitive development causing future difficulties in stress management and stifling creativity and innovation (Gorman, 2017). Sensory integration is regarded as a specialist field within the profession of occupational therapy. A reality in South Africa is that over 60% of the South African population does not have access to sensory integration services (Jaarsveld *et.al*., 2021). Providing children in marginalised communities with sensory-enriched play opportunities can improve their sensory-motor and cognitive development which forms the foundation for successful school performance (Jaarsveld *et.al.,* 2021). Due to a lack of governmental funding, high crime rates and vandalism, as well as a lack of knowledge about the importance of play for ECD, there is a scarcity of safe, public, sensory-integrated playgrounds, especially in under-resourced communities in South Africa (Jaarsveld *et.al,* 2021; UNESCO, 2006). Consequently, due to a lack of appropriate developmental stimulation, research indicates that preschool children in low socio-economic communities present a higher prevalence of sensory integration challenges leading to developmental delays (Jaarsveld *et.al*, 2021; Van der Walt *et al.,* 2022).

This paper presents results from an unpublished Industrial Design BA Honours practice-based research project undertaken at a higher education institution in South Africa (Gibbon, 2023). The project focused on the design of a low-cost, contextually appropriate sensory-enriched playground for preschool children in South Africa. Using a participatory, human-centred design approach, the project applied Design Thinking and Appropriate Technology Theory to develop an innovative solution tailored to the specific context. The outcome, Sensescape, is a cost-effective, easily assembled, and adaptable playground design made from locally available and recycled materials and standard components, enabling the system to be both locally produced and maintained.

RELATED STUDIES

> *"The reality is that children who are raised in poverty or under-resourced environments often lack the opportunity for environmental stimulation and exploration*

and social interaction, which collectively impacts their development. These children fail to develop the abilities that support their writing and reading skills, often resulting in poor school performance and school failure. A lack of successful school achievement feeds into the perpetuating cycle of poverty by limiting opportunities for gainful employment.[…] Building low-cost playgrounds, allowing for sensory-rich experiences, together with the development of balanced sensory enriched programmes to be implemented by educators, could result in addressing this problem" (Jaarsveld, *et al.,* 2021: 10-11).

This project was inspired by and builds upon the findings of the 'Back to Urth' playground research project (Jaarsveld *et al.*, 2021), which aimed to investigate the impact of a sensory-motor stimulation program based on Ayres Sensory Integration (ASI) theory. Activities were designed to be presented by educators to learners, on a specifically designed playground with balanced, sensory-rich experiences that support development. The playgrounds were designed to offer specific tactile, vestibular, and proprioceptive sensory experiences, with each component crafted based on ASI principles. Constructed using low-cost, eco-friendly materials and methods, the 'Back to Urth' playground features ten distinct equipment stations, each addressing different sensory-motor components.

Figure 3: *Back to Urth Playground (Jaarsveld et al., 2021)*

A 12-week program was developed whereby educators were trained on how to present this program on the playground (Jaarsveld *et.al,* 2021). Two non-fee-paying rural schools were chosen for this study. One school had a playground built and the other did not. Over the 12-week study, the learners from both schools did a series of tests under the guidance of the researchers and occupational therapists. The tests, standard tests used to teach motor skills, learning proficiency, and school readiness saw a marked improvement in the results from the schools with the playground compared to those without (Jaarsveld *et.al,* 2021).

While the Back to Urth playgrounds have proven successful, there is significant room for improvement in their construction. The limitation in the design of the 'Back to Urth' playgrounds is that their primary focus was on demonstrating the value and necessity of sensory integration, rather than creating the most effective sensory-integrated playground. These playgrounds often rely on found or donated materials, with a predominant use of tires, gum poles, and concrete for various elements (Gibbon, 2023). The absence of a set design or template means that the skills of individual craftsmen and builders determine the final playground design. This situation underscores an opportunity for creating standardised equipment with clear and easy-to-follow construction instructions. This study therefore builds upon the research conducted by Jaarsveld et al (2021) with a heightened focus on Design Thinking and Appropriate Technology theory with the aim is to create a more suitable, scalable, and effective design that enhances sensory stimulation for playground users.

RESEARCH DESIGN

Problem Statement, Aim, and Objectives

Insufficient opportunities for sensory integration during the ECD phase leads to lower levels of cognitive development. The scarcity of suitable playgrounds in under-resourced communities in South Africa puts ECD-aged children at a higher risk of having sensory integration problems. This study builds on the research done by Jaarsveld et al and the 'Back to Urth' playgrounds by following a Human-Centred Design methodology and applying ASI, Design Thinking, and Appropriate Technology Theory to design a low-cost sensory-enriched ECD playground for children aged 3-6 in under-resourced communities in South Africa.

To achieve this aim, the following objectives were defined:

1. Conduct qualitative data gathering to
   - Develop an understanding of sensory integration during the early childhood development phase.
   - Identify the playground elements/activities that are required to best stimulate and regulate and stimulate the 7 senses.
2. Conduct a qualitative precedent analysis of existing playground designs, playground elements, and sensory-based equipment, through the lens of Design Thinking and Appropriate Technology.
3. Conduct a Thematic Analysis of data gathered in points 1 and 2 to define a design brief/ list of requirements.
4. Follow a participatory Human-Centred Design process to design a low-cost appropriate solution to develop these playground elements in line with the design brief.

Guiding Theories

The guiding theory for this research was Sensory Integration theory, which "emphasises the active, dynamic sensory-motor processes that support movement as well as interaction within social and physical environments and that act as a catalyst for development" (Lane *et al.*, 2019). The primary goal was to forefront sensory stimuli and address the senses for effective and appropriate sensory stimulation and integration as a foundation for future learning. However, the world is a complex place and South Africa has a particularly complex and dynamic social, economic, and cultural ecosystem. When designing a product or service for such a context, which poses many challenges and nuanced considerations, designers must develop a deep understanding of the subject, context, users, and community for whom they are designing. To achieve this, the project was guided by the theoretical underpinnings of Design Thinking (DT) and Appropriate Technology (AT), two prominent human-centred design theories that prioritise understanding the needs, preferences, and capabilities of the users or community for whom the technology is intended. DT is a human-centered approach to innovation that integrates three dimensions Desirability, Viability, and Feasibility. According to DT, the success and sustainability of a product or service hinge on addressing and considering all three dimensions effectively in the design process (IDEO, 2015). AT theory, on the other hand, considers a technology to be appropriate when it aligns with local, cultural, and economic conditions, utilising locally available materials and energy resources while being operated and controlled by the local population (Hazeltine & Bull, 2003). When designing for children, safety must also be taken into consideration. Both theories recognise the importance of context. DT encourages designers to empathise with users and understand the broader context of product or service usage. Similarly, AT emphasises designing solutions that are relevant to the local cultural, economic, and environmental conditions.

The principles from each theory were integrated and synthesised to form six dimensions/lenses namely Sensory Integration, Safety, Material and Manufacture, Cost, Adaptability, and Sustainability. These lenses were defined and utilised to research, ideate, evaluate, eliminate, and develop concepts throughout the process of creating a solution that not only meets the specific needs of a community but also aligns with the local context and promotes long-term sustainability.

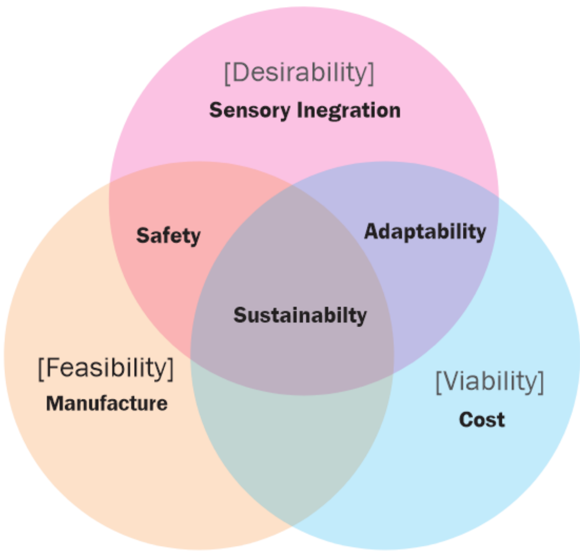

Figure 4: Six lenses of design considerations (Authors)

Methodology

This study followed a participatory Human-Centred Design (HCD) approach (IDEO, 2015). HCD seeks to deeply understand users' needs, behaviours, and experiences to create effective solutions. However, ethical considerations prevented the direct involvement of the intended users, children aged 3-6, in this study. Consequently, this study directly engaged with purposively sampled expert ECD professionals. Employing qualitative data gathering and analysis tools, the research aimed to discern and articulate the requirements of the designated end user through their experience, observation, and expert knowledge of the topic. This study consisted of three main phases namely Inspiration, Ideation, and Implementation (IDEO, 2015). Below we provide an overview of the methods and activities undertaken in each phase for achieving the predefined research objectives.

The inspiration phase involved gathering and analysing qualitative data, leading to the formulation of a design brief. To achieve Objective 1, a thorough investigation was conducted, involving both primary and secondary data collection. Secondary data was obtained through extensive desktop research and an in-depth literature review, covering topics such as sensory integration theory, early childhood development, the South African ECD context, and related studies. This process laid the groundwork for a foundational understanding of the subject matter, the identified problem, and the underlying opportunities. Primary data was gathered from three Occupational Therapists (OT) through interviews. To achieve Objective 2, we conducted a thorough precedent study through field research, visiting different schools and public learning centres. This involved a detailed analysis of various equipment used, employing the six lenses to assess the strengths and weaknesses of each element. To analyse and make meaning of the qualitative data, a six-step Thematic Analysis (Braun & Clarke, 2006) was conducted, which ultimately led to the formulation of a design brief, serving as the foundation for the subsequent ideation phase.

The first step of the Ideation phase involved a co-design process with school children whereby they were asked to draw or visualise their ideal playground. This exercise was facilitated by the teachers, and not the researcher due to ethical considerations. Analysing these drawings highlight core values for the children (Desirability). Insights from these drawings highlighted the children's love of nature and togetherness, rarely depicting individual play. These insights were added to the design brief as considerations. Next, several concepts were generated through sketching and Post-it note brainstorming to rapidly explore and ideate a wide variety of concepts. Each concept was assessed and filtered through the six lenses of sensory integration, safety, material and manufacture, cost, adaptability, and sustainability. The most suitable concepts were selected and developed further through sketching and CAD modelling and then presented to a focus group of four teachers at a local preschool for feedback. Using a series of activities and worksheets teachers provided feedback and design input then further facilitated a participatory ideation process. This process resulted in a narrowed-down product family of specific elements. Thereafter, an iterative process of prototyping, user testing, feedback, and refinement followed.

Finally, the Implementation phase involved the prototyping, making, and testing of the final design and receiving final feedback from the participant group.

RESULTS AND DISCUSSION

The outcome of the above-described HCD process, Sensescape (Figure 3), is a series of sensory-enriched playground elements designed for children aged 3-6 in under-resourced and rural communities in South Africa. Building on the work of "Back to Urth" playgrounds designed by van Jaarsveld and her team, Sensescape has been designed with careful consideration for sensory integration, grounded in contextual considerations. The resultant 13 pieces of equipment are low-cost, easy to assemble, and allow children to be exposed to sensory input in a balanced and regulated way. The equipment can be used individually or as part of a complex obstacle course. The elements are well suited to any park/site/field in South Africa and do not require a flat surface like many alternative jungle gyms and playground equipment systems. This section provides a detailed description of the design and its components.

Figure 5 Sensescape playground elements (Gibbon, 2023)

The research findings identified the following 4 categories of play: Active Play, Block Play and Pattern Play, Sound and Tactile Play, and Sand, Water, and Ball Play. The design process involved reflection and analysis, leading to the removal of certain components like sand, swings, slides, and pipes. The playground is specifically tailored for under-resourced communities in South Africa, where challenges like lack of clean water, funding for maintenance, and barriers to prevent stray animals are common. Water play and sand play were excluded due to issues of wastefulness, hygiene, and difficulty in maintenance. Sound pipe assemblies and concrete sound blocks were considered but were deemed impractical due to complexity, transport difficulties, and cost. Slides and swings were also omitted due to transport challenges, maintenance difficulties, and concerns about hazardous materials. Block and pattern play, while valuable for early childhood development, was excluded from the outdoor park design due to potential misuse. Active play components were prioritised in the refinement phase for their alignment with sensory integration and overall developmental benefits. The 13 selected active play and sensory elements include a suspended balance beam, suspended walking paths, tunnel shelter/tent, pole path, rope climber, swing set, bead curtain, balance wire, static balance beam, long see-saw, short seesaw, and climbing pillars.

After ideating the various balance, movements, and activities that would be suitable to fully engage the proprioception and vestibular systems it was identified that they all tend to involve or require a frame-like structure. It was essential to consider the material, assembly, and construction of the frames as the foundation of the playground design.

While steel frames were initially considered due to their strength, durability, and weldability, their high cost, weight, and specialised assembly tools led to exploring wood as a more feasible alternative. Treated gum poles, commonly used for standard jungle gym design and construction, were selected for their durability, affordability, and accessibility. This choice provided a consistent and feasible approach to manufacturing, enhancing the overall viability of the design. However, practical mock-ups revealed various unanticipated challenges. Aligning the drill for accurate hole placement through the dense gum poles proved difficult, especially when working on the ground. Cutting the poles safely required a dedicated vice and workbench, with a circular saw identified as a more suitable tool than a handsaw. Additionally, variations in gum pole diameters (ranging from 75mm to 100mm) and lengths posed challenges for consistent and reliable structure construction, potentially leading to variations in strength or wasted material in future orders. For this reason, it was decided to use square profile locally sourced CCA-treated pine.

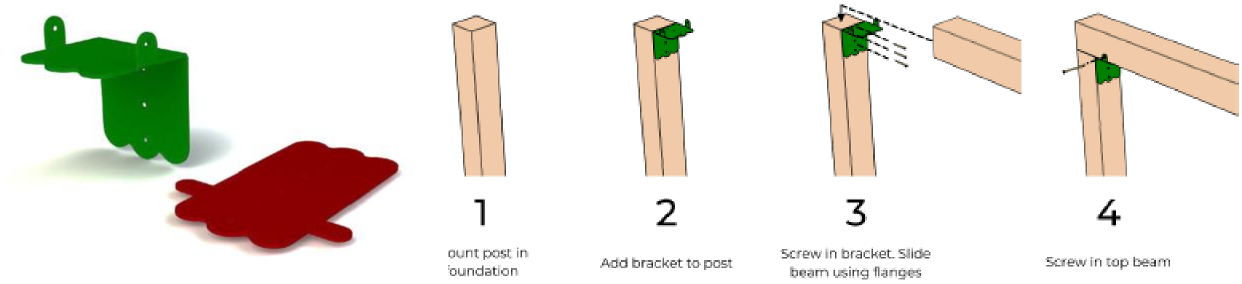

Figure 6 Bracket Assembly steps (Gibbon, 2023)

Ease of transport, ease of on-site assembly and installation, along with strength and durability were key priorities in the design of the frames. To improve usability and avoid user error in installation (as experienced with the gum poles described above) a specialised, locally manufactured bracket (Figure 4) has been designed to ensure construction is as easy and efficient as possible. The bracket is waterjet cut from 3mm steel with one large 90-degree bend and 2 smaller 90-degree flanges. The two flanges allow the top beams to be positioned neatly above the vertical post. This ensures an accurate 90-degree corner. The timber rests on the vertical post providing maximum vertical load support for when the equipment is in use. The two small flanges each feature a screw hole offset from the other screw holes to ensure no accidental collisions of screws. Countersunk holes ensure the screw heads are hidden and won't be a risk to the users.

The Sensescape system comprises two main frame designs. The large base frame is used for the suspended balance beam, tunnel, shelter, and walking path (Figure 5). The small frame is used for the pole path, rope climber, swing set, bead curtain, and balance wire (Figure 6). There are four smaller additional structures: Static Balance beam long and short See-saw and Climbing pillar (Figure 7).

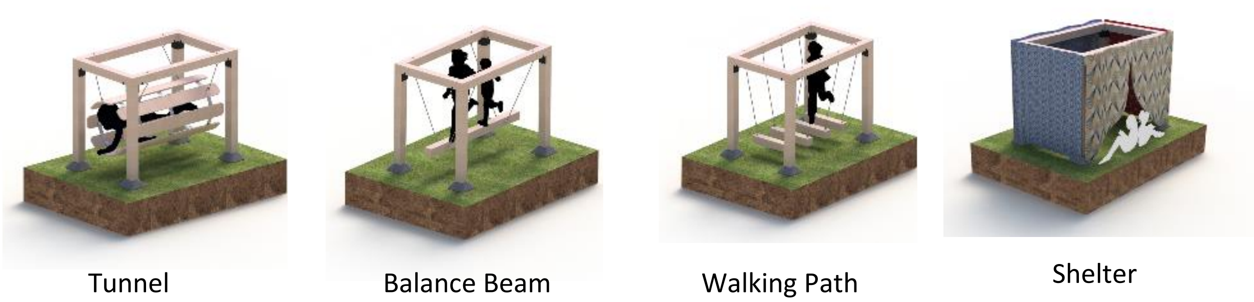

Figure 7 Large Frame Elements

Figure 8 Small Frame Elements

Figure 9 Additional Elements

REFLECTION

To evaluate the success of achieving objective 4 and the main aim of the study, this section provides an evaluation of how the Senscape outcome has aligned with or addressed the 6 lenses/ requirements.

Sensory Integration
Sensescape is a thoughtfully curated system of playground elements designed to enhance sensory integration in children. Each element is meticulously chosen and crafted to engage specific senses, providing enriching sensorial experiences. The Proprioception and Vestibular sensory systems, though less recognised, play crucial roles in early childhood development and physical growth. Sensescape equipment becomes a platform for children to learn and explore aspects such as balance, body position, walking, running, climbing, grip strength, and dexterity. Sensescape's diverse challenges and difficulties encourage learners to explore their capabilities, limits, and abilities. A notable example is the climbing wall, featuring a 4-sided Rockhold that can be rotated to increase the challenge for each learner.

Material and Manufacture
The playground equipment is designed with careful consideration for material quality, manufacturing efficiency, and ease of assembly. A custom steel bracket, precision-cut from 3mm steel, simplifies installation with a 90-degree bend and flanges. The bracket's width aligns seamlessly with the timber, and the flanges aid in the precise placement of top beams over

vertical posts, ensuring accurate alignment and robust vertical load support during usage. All treated timber beams are uniform in length (1600mm), minimising unnecessary cutting and logistical complexity. Longevity and durability are prioritised, utilising standard eyebolts readily available at local hardware stores. The long beams feature evenly spaced holes for attaching eye bolts, accommodating various elements such as swings, balance beams, and paths. A laser-cut template in the kit indicates the 320mm spacing for eye bolts and 50mm hole spacing for specific elements like see-saws, bead walls, pole paths, and moving platform cross beams. The kit includes an instruction manual for comprehensive guidance for installation.

Safety
The Sensescape system prioritses safety, especially for children, by South African National Standards. The design, frame, manufacturing processes, and bracket design ensure structural integrity and eliminate hazards like splinters. The system adheres to regulations specifying durable materials for playground equipment. Most notably, to address the common risk of falling, Sensescape elements have no fall height above 400mm, well within the maximum 600mm fall height standard.

Adaptability
Each site or playground will offer significantly different requirements. To address varied terrains, layouts, and sizes of playgrounds, this system consists of 13 freestanding elements installed individually with pile foundations. This approach unlike the alternative of casting a concrete base, requires less preparation/ landscaping and simpler installation this method aligns the posts with each other rather than the ground, allowing flexibility for uneven surfaces. Furthermore, the construction of the suspended elements cables can be slightly adjusted in length to accommodate gradients or uneven ground conditions.

Affordability
As mentioned above, Sensescape is designed to be made from locally available, standard materials and hardware. This allows for ease of maintenance and repair. The modular/adaptable nature of the playground elements makes the solution scalable to the budget of the community/school/ NGO which also impacts the affordability of the playground.

Sustainability
Social sustainability is addressed on multiple levels. Initially, the provision of a safe and accessible play space for children in underserved communities adds value to the lives of both children and families. The design of the playground is low-cost, easy to maintain, and offers opportunities for local job creation, thereby fostering local ownership and facilitating ongoing maintenance of the playground. Economic sustainability is addressed by carefully considering costs, the availability of materials, and ease of maintenance. Finally, environmental sustainability is considered using durable materials, minimising waste in manufacturing, and incorporating recycled plastic in the bead curtain element.

Recommendations for further study
This project was conducted at an Honours level, yielding valuable insights and considerations. The authors recognise the need for additional development, testing, and refinement to establish the validity of the design outcome. The primary focus of this paper, however, was not to assert the outcome's validity but rather to highlight the value of the proposed hybrid model in the development of contextually appropriate outcomes. The collaborative integration of expert knowledge with contextual considerations resulted in an effective and innovative design solution that successfully meets five out of six specified requirements. Nevertheless, the

Authors acknowledge that substantial further testing, investigation, and business planning are essential to validate or enhance the affordability and viability dimension. This includes considerations of cost-effectiveness in the intended context, identifying responsible parties for construction and maintenance, and refining the business plan and implementation strategy. The Authors propose that continuing this research in a master's study would provide the opportunity for continued exploration and development.

CONCLUSION

The paper argues that access to quality early childhood development (ECD) in South Africa is currently inequitable, especially in under-resourced communities. Playgrounds play an important role in effective sensory integration, which is critical for cognitive development during the ECD phase. The lack of publicly available sensory-integrated play spaces in under-resourced communities in South Africa can result in underdeveloped neural pathways leading to future academic, social, and emotional difficulties for children. The paper presents a low-cost, easy-to-assemble, adaptable playground design, called Sensescape, crafted from locally available and recycled materials and standard components, enabling the system to be both locally produced and maintained. The project applied Design Thinking to develop a contextually appropriate innovative solution employing a participatory, human-centred design approach.

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GROWING FOOD SECURITY: A PROPOSED FRAMEWORK FOR SUSTAINABLE AND APPROPRIATE INNOVATIONS FOR SMALL-SCALE URBAN FARMING.

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ABSTRACT

UN Sustainable Development Goal (SDG) 2 aims to create 'a world free of hunger by 2030'. However, as food insecurity continues to intensify on a global scale, particularly affecting marginalized communities in developing countries such as South Africa, we are at a critical juncture. Small-scale urban farming (SSUF) can contribute to food security by increasing local food production and enhancing the accessibility and distribution of fresh produce in marginalised communities. SDG2 Target 2.3. seeks to double the agricultural productivity of small-scale food producers by ensuring they have secure and equal access to land and resources. SSUF, however, faces numerous challenges. Effective resource management and access to appropriate off-grid technologies are issues faced by many SSUFs in South Africa and similar developing contexts. This has been identified in this paper as an opportunity for an industrial design intervention. Developed for a practice-based MA Industrial Design research project, this paper presents a proposed theoretical framework for the development of sustainable and appropriate innovations for SSUF in developing contexts. The authors provide a contextualisation of the problem and project focus to frame and justify the proposed hybrid approach. We then provide an overview and discussion of the guiding design theories of 'Appropriate Technology,' 'Design for Sustainability,' 'Design for Socio-Technical Systems,' and 'Participatory Design'. While each theory individually contributes to the project, we argue that a hybrid framework is necessary to successfully and sustainably address the identified problem. We conclude by providing a detailed description of the hybrid framework. While this framework was utilized in a study focused on the development of an organic matter processor, the primary aim of this paper is not to document the project's outcomes through the application of the model. Instead, we seek to motivate the need for such a hybrid theoretical model and its suitability for application to various appropriate technology innovations in SSUF.

Keywords: Food Insecurity, Appropriate Technology; Sustainability; Design for Socio-Technical Systems; Participatory Design

INTRODUCTION

Solving the global challenge of hunger by 2030, as envisioned by the United Nations Sustainable Development Goal 2 (SDG2), stands at the forefront of our collective responsibility. According to the UN Food and Agriculture Organization (FAO, 2023), between 690 and 783 million people faced hunger in 2022, 122 million more people than before the COVID-19 pandemic. Nowhere is this crisis more palpable than in marginalised communities in developing countries like South Africa where food insecurity continues to escalate and around 90% of the population is food insecure (Oxfam 2014a). Small-scale urban farming (SSUF), has the potential to improve food accessibility, distribution, and quality within these societies, while concurrently providing a myriad of social and economic benefits. However, productivity on these farms has been somewhat underdeveloped (Shisanya & Hendriks 2011: 510). Issues of food insecurity are closely linked to the accessibility of farming technology (Shisanya & Hendriks 2011: 511). SDG2 Target 2.3 specifically calls for the doubling of agricultural productivity among small-scale food producers by ensuring they have secure and equal access to land and resources.

To define urban farming we refer to Mouget (2000: 11) who wrote:

> "Urban agriculture is located within or on the fringe of a town, a city or a metropolis, and grows or raises, processes and distributes a diversity of food and non-food products, uses largely human and material resources, products and services found in and around that urban area, and in turn supplies human and material resources, products and services largely to that urban area".

SSUF can range from subsistence to commercial depending mostly on spatial, equipment, and human resources. Small-holder urban farms produce approximately 80% of the world's food in terms of value (FAO 2023). The FAO (2014) attribute this to local farmers leveraging their intimate ecological knowledge, applying a localised understanding of their soil, flora, climates, and fauna species to successfully optimise yields and therefore work in harmony with nature for what is mutually beneficial for a productive life. SSUFs have access to local supply chains but often fall short in scales of production and supplying points of sale with sufficient stock (McLachlan & Thorne 2009: 18). An opportunity therefore exists to enhance this connection to economic activity by increasing production. Issues of access to resources, resource management, and the adoption of suitable off-grid technologies are paramount concerns in SSUF in South Africa. Attempts to improve access to technology often take the form of government grants and external aid programmes, yet food insecurity continues to intensify (McLachlan & Thorne 2009: 4). External aid often proves to be unsuccessful in introducing technology to marginalised communities as it fails to consider important aspects of the context, rendering the users dependent on the external source (Schumacher 2010: 141). Closed-loop and integrated resource management approaches could address various challenges facing SSUF (Bisaga, Parikh & Loggia 2019).

SSUF in South Africa faces various challenges such as limited access to resources, financial constraints, and a lack of infrastructure. These challenges hamper the efficiency of SSUF operations. Addressing such challenges requires a multi-faceted approach to innovation that empowers SSUF to achieve self-sufficiency and autonomy.

CONTEXT

A significant challenge facing food security and food production globally, is soil infertility (Bunch 2012: 21). Balanced agricultural soils comprise an array of macro and micronutrients and an infinite number of active microorganisms that thrive in these environments whilst performing the essential function of micro-scale recycling of organic matter (Herring 2010:1). However, limited moisture and insufficient organic matter are common issues found within soils in semi-arid and urban settings within the Sub-Saharan (Hazeltine & Bull 2003: 289; Bunch 2012: 26). According to The Council for Scientific and Industrial Research (CSIR), South Africa loses an estimated 300 million tonnes of topsoil per year due mainly to soil infertility and subsequent erosion and degradation. Retaining moisture in agricultural soil in semi-arid regions is critical for soil fertility, crop productivity, and sustainable water consumption.

This paper presents a theoretical innovation framework developed for a practice-based MA Industrial Design research project process that aimed to design an appropriate, sustainable organic waste management model for the University of Johannesburg's Bunting Road Campus, in South Africa. An ecological research unit (The Centre for Ecological Intelligence) has erected three growing tunnels on the campus near the student centre and student residences. One of the tunnels is currently being used to grow hydroponic seedlings using high-tech methods. The second is being used for small-scale, low-tech input (traditional) farming methods. The third is currently being under-utilized as an experimental area for students' and fellows' innovative technology developments, which aim to support efficient organic food production in various ways. A preliminary investigation into the wider campus ecosystem indicated an opportunity related to the management of the organic matter on campus that is currently considered waste. According to the Facilities Management Department, excess organic waste (such as offcuts from weeding and tilling the general vegetation) is laboriously managed only to be moved off-site, by an external contracted company, to a dump about 15km away. An estimated 30 tons of garden waste is removed from the campus per month, at a hefty fee. Urban farmers in Johannesburg are located in the parched Highveld, an inland plateau. There is an opportunity to create valuable organic soil/plant feed from waste material that is currently a liability to the university. We hypothesise that effective waste (resource) management could produce high-quality plant feed/soil, essential for producing nutritive organic produce in larger quantities, making the farm more successful and productive, and benefiting the campus ecosystem in various ways such as enhancing synergistic links between stakeholders and positively tapping into the campus's food system, which predominantly offers highly processed, nutrient weak food.

Acknowledging the complexity of the context, stakeholders, and the larger ecosystem, we believe such a project requires an innovative, participatory approach to achieve a sustainable and successful solution. In this paper, we elaborate on four prominent Design Theories and approaches namely: Design for Socio-Technical Systems, Design for Sustainability, Appropriate Technology, and Participatory Design. While each theory shows suitable linkages to the project, we argue that a hybrid framework is necessary to successfully and sustainably address the identified problem and opportunity. We conclude this paper with a description and motivation of a proposed hybrid model and a description of its intended application.

DESIGN FOR SOCIO-TECHNICAL SYSTEMS

This theory has evolved over a period of about six decades. It can be simply defined as an approach to designing organisational systems by considering not only technical aspects but also human, social, and organizational factors (Whitworth 2009: 394). There is a seeming gap in this theory, where nature is not mentioned in the title. This study notes that together with sustainability theories, and the inherent needs of people, nature must be considered. The living context is therefore often holistically referred to as an ecology rather than just a society. Feenberg (1999: 2) recognises design as an instrument to manifest the position of power held by a group of people in society. The design process can only be considered truly democratic once the technology is appropriately integrated into society. The application of this theory could therefore largely benefit the stakeholders within the ecosystem of this study. Actors or participants/users adapt and transform the design when this integration is incorporated into the process, thereby truly taking ownership of it (Feenberg 1999: 206-208, Leavitt 1965), often resulting in more appropriate technology (Feenberg 1999: 124). Leavitt (1965) acknowledged the interaction between variables of the system elements named as, the structure, technology, actors, and task. This ecosystem was further developed and visualised by Valdez and Brauner (2016: 484), to position these system elements within a broader organised system (*Figure 1*, adapted by author). German philosopher of technology, Günter Rophol (1999) borrows the concept from labour studies of the 1960s where it was used to describe the interaction between human behaviour and society's complex infrastructure (Emery & Trist 1960). Rophol (1999) uses a systems model to describe socio-technical innovation. He describes it within socio-technical systems as "both social and technical phenomena, persons and machines, the technization of society and the socialization of technology". By encapsulating the theory within a system, he links the act of invention to social change:

> "Every invention is an intervention, an intervention into nature and society. That is the reason why technical development is equivalent to social change" (1999).

Another limitation of socio-technical system innovation is that it can be too "big picture" (Ceschin & Gaziulusoy 2016: 141), which suggests that the study's framework needs more support from other approaches. To further guide this innovation and research framework, theories of Appropriate Technology and Sustainability were chosen, to better align the research and development results within the local context. This design approach is therefore strategically framed with these multiple theories encapsulated within urban ecological systems.

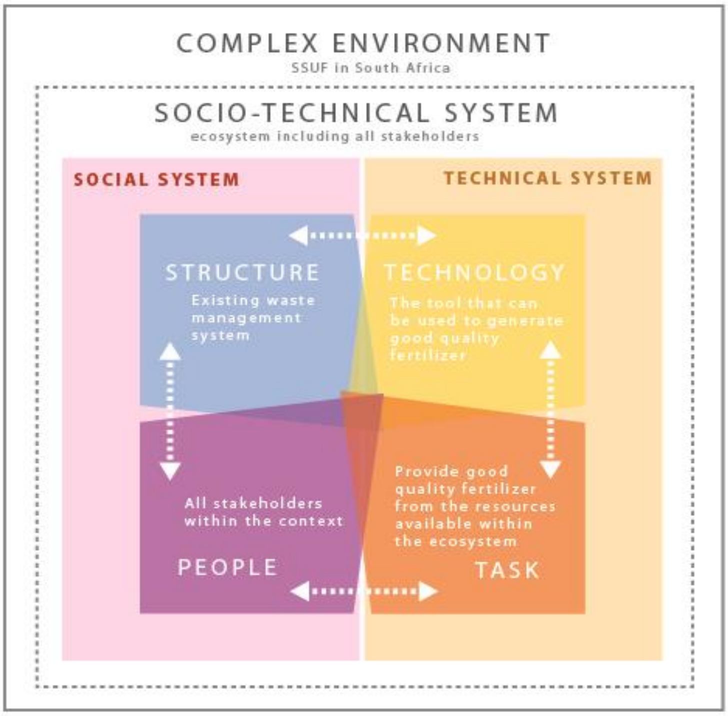

Figure 10 Socio-technical system model, 2016 (Valdez & Brauner, 2016, p. 484) (Adapted by Author 2023).

APPROPRIATE TECHNOLOGIES

According to Hazeltine and Bull (2003), a technology is deemed appropriate when it aligns with local, cultural, and economic conditions, utilising locally available materials and energy resources while being operated and controlled by the local population. There is a global course that favours the rich getting richer and the poor getting poorer. Foreign aid within the context of developing countries tends to support this trajectory. This is resulting in accelerating decay in developing countries (Schumacher 2010: 141). There is a need for socio-economic growth within these contexts. To meet this need as well as the basic human needs of civilians, it is required that the emergence of innovations must focus on meeting the needs of the small-holder farmer, small-scale rural industry, and the informal sector producer from within the context (Hazeltine & Bull 2003: 5). This study aims to harness this advantage of this theory to foster innovative growth in the form of technology that meets well with the system and people of where it is located. Within the realm of manufacturing, there is a need for the exploration of small-scale and more decentralised organisations to realise substantial material growth that benefits ordinary civilians (Schumacher 2010: 144). To meet these needs, the production methods must consider what is locally available for manufacture as well as repair processes and simple production methods to not demand a high level of skills/training or monetary input and thus render ease of accessibility. This therefore results in a product that is self-sustaining within its system. Hazeltine & Bull state that another guideline for appropriate technology is promoting local business opportunities and social growth (2003: 9). There should be a conscious effort to implement the technology through co-development and participatory methods to ensure appropriate applications within the context (Schumacher 2010: 145).

An important aspect of this type of process is transparency. This is a potential risk in using this theory, as it may not be carried out honestly and openly enough in practice. Although it is important to ensure the design performs well, it is just as important to continuously explain what it is to all parties involved for ethical reasons and to stay true to participatory methods by allowing design input, primarily from the ecology. If this is not done properly, there could be missed opportunities in terms of the features of the design or how well it relates to the participants at that moment as well as its ability to morph in synchronicity with the users and the environment. It is therefore important to use this theory whilst staying true to participatory methods of design and research development. Studying the ecosystem through a socio-technical lens will assist in providing a detailed map to avoid nuanced oversights. The value impact should be demystified through the process of engagement (Lasky 2013: 24). All stakeholders can thus authentically engage in the process how they feel is appropriate and thereby claim their stake. The entire design development from problem conception to product realisation should then be open to this emergent process. “It is more about integrating a holistic and systems approach into existing disciplines that are involved in socially responsible design” bringing local community members into the arena and building a culture of open evaluation (Lasky 2013: 33). This results in a product that is not created to be definite in a system, but to be able to live within a system and morph to suit its aspects as it evolves, empowering the users to do so, allowing the product to thrive independent of external aid. It is evident how this theory is an overarching goal in the research that can largely assist the outcome to be as suitable as possible.

A limitation of this theory is that the implementation and practice may not go as planned as there may be a factor that was not considered. This is typical in the design development process where a certain context is in the process of being understood. Iterative realisations are an effective way of prototyping and reassessing the solution as many times as possible. This is why this theory pairs well with participatory methods which embrace and promote iterative applications. This research aims to embrace the theory that is currently understood to be appropriate technologies and use it as a platform to engage and console with other theories that overlap with similar thinking and discourse. The additional emerging theories that have been included bring insights that combine well with what is found to be appropriate within the problem frame.

DESIGN FOR SUSTAINABILITY

The concept of sustainability has evolved significantly over the past four decades as it has strived to keep up with a fast-changing world. Many of its shortcomings have been addressed in recent years. Initially, sustainability was an all-encompassing, global term with an emphasis on the environment, acknowledging that society is dependent on the environment and its resources (Ceschin 2016: 118). The term was coined in 1987 in the well-known Brundtland Report: 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED 1987: 43). More recently, it has been realised that a more dynamic approach is required (*figure 2*). Our understanding of interdependencies between social and ecological systems is evolving. To attend to and acknowledge the complexity of this interdependence, it is more appropriate to apply the concept of temporal and spatial indicators that are context-specific (Faber et al 2005: 22). The notion of sustainability is in motion from the insular product level towards a more systemic, integrated socio-technical system level (Ceschin 2016: 144).

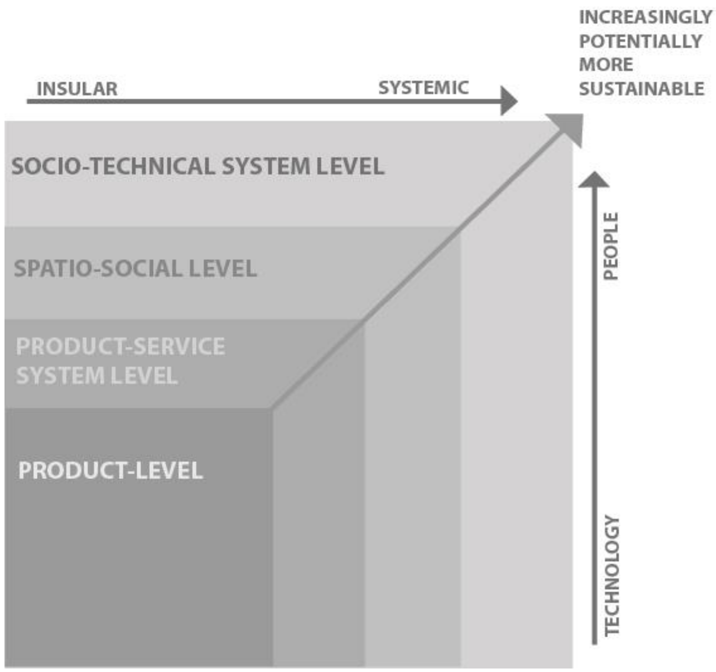

Figure 11 Design for Sustainability Evolutionary Framework 2016 (Ceschin & Gaziulusoy, 2016, p. 143) (Adapted by author).

Recently, the topic of sustainability-oriented innovations has pointed toward environmental and social benefit projects focusing on process-centric, large-scale system-level changes rather than narrow, technical, product outputs (Ceschin 2016: 141). There is a compelling global urgency for radical change within our societal systems to mitigate and adapt to climate change (Hughes et al 2013: 9). As the definition of sustainability is now beyond anthropometric needs, we have been forced to consider the extent of terrestrial, aquatic and biodiversity decline (Ceschin 2016: 119). This radical transformational change is required in the form of innovative, appropriate technological interventions as well as social, cultural, and behavioral changes on an individual and organisational level (Ceschin 2016: 119). Design has been identified as a primary agent for innovative change in many social and technical systems, and most relative to this framework, locally within urban ecologies (Ceschin 2016: 119). Any solutions that emerge from this study must adhere to the requirements of sustainable design to not be destructive or obsolete within the world.

Various approaches and tools have been identified within the current theory of design for sustainability (DfS) that form parts of the theoretical framework; Design for Sustainable Behaviour (placing people at the center of the process) (Sherwin 2006: 26), Design for System Innovation (conducting a life cycle assessment and mimicking ecosystems of nature) (Sherwin, 2006: 23), Design for the Base of the Pyramid (following bottom-up approaches and activating roles for users to participate in the design process as co-creators) and Design for Sustainable Social Innovation (supporting the facilitation of the process of replication and scaling up) (Ceschin 2016: 126). These theories and their corresponding strategies will form part of the approach that guides this research process and its practice. Within the topic of design for sustainability, the concepts of regenerative processes (Ceschin 2016: 126) and the circular economy have been identified as key points. Design can provide support to strategically selecting materials and designing products that foster closed-loop material flows within a system (Fletcher & Grose 2012: 98). Thereby promoting a shift from consumption based on ownership to consumption based on access, sharing, and integration within an ecosystem (Ceschin 2016: 131). As the theory of sustainability has changed significantly over the past four decades, it is important to avoid some previous downfalls of this theory that occurred in the past. This is done by focusing on the wider, ecosystem-level approach that aligns with spatial and temporal consciousness also found in socio-technical theories and applications as well as resource consciousness found in appropriate technologies.

PARTICIPATORY DESIGN

This theory offers a set of coherent concepts and articulations for exploring the true nature of a problem by finding information that exists within the context (Dalsgaard 2014: 145). The above-described theories all call for an in-depth acknowledgment of the design context in terms of the broader ecosystem, the stakeholders, and the local context for which the product/service is intended (Schumacher 2010: 145). It is therefore required that the methodologies for conducting the research acknowledge these elements. Participatory design processes allow for the development of products and concepts to evolve together with the users and key stakeholders so that the result fits with what the users want and what the system requires to operate more efficiently (Akubue 2000: 38, 39). Conducting Participatory methods is about stimulating processes of communication, cooperation, and creativity (oxfam *et al* 2008: 280). This approach should be incorporated throughout the process of design, evaluation, and implementation. The result is then more likely to be adopted and sustainable within its context and therefore more appropriate (Pals *et al* 2008: 275). This method aligns with the more systemic trajectory of sustainability, an integrated socio-technical system-level approach. In 2010, IDEO created a Human-Centred Design (HCD) toolkit that has been used widely by designers since. HCD tools are flexible and complement participatory methods that seek to appropriately engage with complex ecosystems and their stakeholders (2010: 12). Krippendorf (2006: 31, 32) explains that this approach gives benefactors a sense of ownership as opposed to forms of techno-centered design. Design criteria, rather than being pre-determined should be informed through emergent participation with key stakeholders within their context, using participatory research methodologies (Pals *et al* 2008: 275). The solution will thus be informed by its context and therefore more likely to be adopted within the system and systems alike. This process is designed to help researchers and designers jointly make decisions where the roles of 'designer' and 'host' are switched at various times (Pals *et al* 2008: 277). This framework can be collectively viewed as a context for modality for sharing real-time technical knowledge to all the stakeholders to render them as beneficiaries by being able to make informed decisions and design developments.

PROPOSED THEORETICAL MODEL

At its core, the proposed hybrid framework champions a Participatory Design approach supported by the principles of Appropriate Technology. These are general methods that are mutually informed and inspired by the theories of Design for Sustainability, and Design for Socio-Technical Systems. Thereby acknowledging that there will always be more space to participate better and more appropriately. It is an attempt to improve all the mentioned theories to enhance the scaffold of a growing framework.

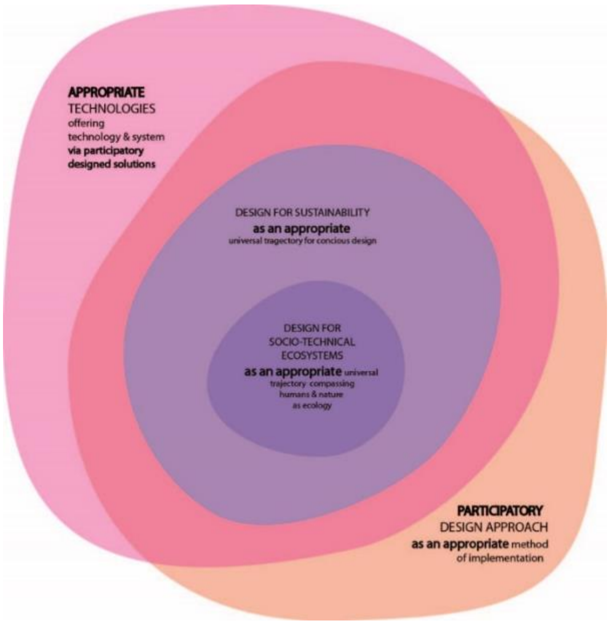

Figure 3: Research framework generated by author. 2024.

Socio-technical systems theory aims to design systems that are adaptable to complex and changing social environments such as “culture, organisation, the context of use, usefulness, policies, and regulations” (Ngowi & Mvungi, 2018: 310). The application of this theory using participatory methods is suitable for this framework due to the complex socio-technical system that became evident within the South African context of SSUF as well as similar developing urban contexts. Much like participatory design, it has been suggested that a socio-technical approach should lead to solutions that deliver better value to stakeholders and are more acceptable within the system context (Baxter & Sommerville 2011: 4). A noteworthy limitation of appropriate technologies lies in its emergence, heavily reliant on the socio-technical context in which it is implemented. Consequently, it is deemed unsuitable for a standalone application. To overcome this, it has been coupled with socio-technical systems theory and integrated into design research and participatory applications. The theory of Design for Sustainability (DfS) is dynamically evolving alongside the world's exponential progress and escalating challenges in combating the impacts of industrialization. However, DfS has yet to attain a level of effectiveness proportionate to the demands of this ever-changing landscape of innovation. The literature review has highlighted the advantages and shortcomings of each theory and advocates for a hybrid model where the chosen theories support each other, resulting in a more stable approach than any of the theories in isolation. The strategic combination of these theories deliberately aims to capitalize on their respective strengths to offset each other’s weaknesses, as explained in each section.

CONCLUSION

The proposed theoretical framework (figure 3) was formulated to serve the implementation of appropriate technology and system design using a participatory method and iterative design practice. Further research will involve the application of this model in the design of a waste and resource management system within the context of an SSUF in Johannesburg. The efficacy can then be assessed and improved through iterative assessments. Inspired by the IDEO Human Centred Design (HCD) stages, this study will consist of 3 phases; Hear, Create, and Deliver (figure 4). Context mapping, participant sampling, and key stakeholder engagement will guide the detailed research and design process. The application of this theoretical framework is still in progress. As this is an ongoing project, the authors have included an example (figure 4) of mapping and some results thereof as visual demonstrations of what this may look like during the process of such a project.

Although the validity of this framework is based on empirical studies of the relative practice theories, it is imperative to sustain this validity through the application of ongoing emergent research as well as gain validity through, ideally, a continuum of returning to the iteration of technology implementations. This asks for a further research paper that documents this model as a case study that would showcase specific technology artifact outcomes. It is recommended that this be showcased as a medium-term or longitudinal study.

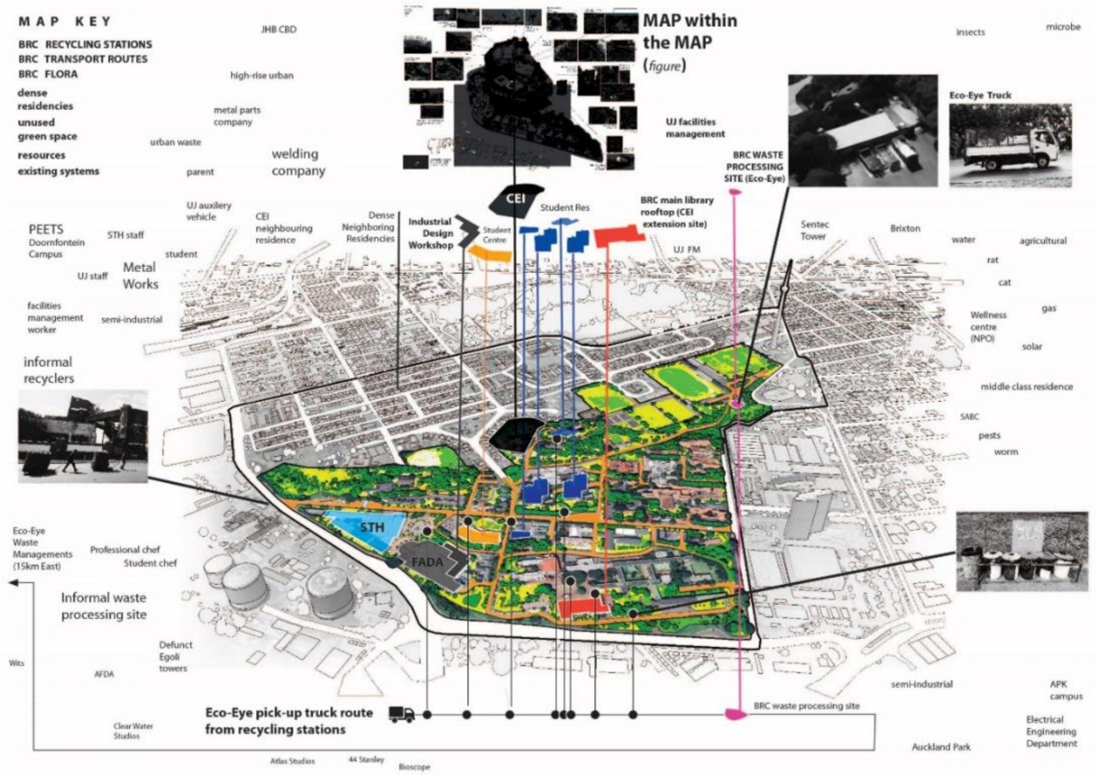

Figure 4: Example of early stage mapping. Showing a broad ecology map (UJ BRC campus in an urban ecosystem) and a localised (figure 6) map (CEI within the BRC) within the map.

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PROJECT MANAGEMENT FRAMEWORK FOR A CIRCULAR ECONOMY

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ABSTRACT

Most economic processes of development, production, distribution, and utilisation operate linearly. Linear economies generate waste. Technological advancement expands economic growth. More people should benefit from technological advances and economic growth. However, if this growth comes with an expansion of waste, we will have problems with environmental degradation, reduced quality of life and unsustainability. The solution is waste reduction through a circular economy. Waste must be eliminated or repurposed. This requires engagement across supply chains. This study starts with the examination of project management strategies that engage supply chains. Advancing a circular economy involves adjustments across the supply chain from extraction of raw materials to product delivery to the final customer. The reduction and repurposing of waste along each stage of the supply chain is key. This study aims to draw on project management strategies to devise a general-purpose framework for engaging infrastructure projects to promote a circular economy. A system dynamics methodology establishes the key variables and causal relationships that are the basis for constructing the framework for promoting a circular economy. More effective infrastructure project management will benefit both rural and urban communities.

Keywords: circular economy, supply chain, project management, system dynamics

INTRODUCTION

One of the core objectives of the International Network on Appropriate Technology (INAT) is to influence technology policy (Trimble, INAT 2015). Technology policy that contributes to empowering people and local communities is essential to improving the living conditions of poorer communities and deprived individuals. Global inequality is driving people to cities. An agenda to address the growth of urban areas as well as small cities in rural settings can benefit from a system thinking world view. While the workers and owners of capital are the key stakeholders in production processes, other stakeholders are identified that impact technology policy. Considerations must be made on how each stakeholder category can be influenced to contribute toward a circular economy agenda.

Appropriate technology policy focuses on delivering basic needs. Food production and distribution as well as other needs, such as water and sanitation, healthcare, housing, transportation, and energy are linked to the development of the infrastructure to deliver these goods and services. The Global Infrastructure (GI) Hub, a non-profit organisation created by the G20 revealed that infrastructure consumes around 60% of the world's materials and infrastructure contributes around 10% of global greenhouse gas (GHG) emissions through construction alone (and 43% during operations) (DelRio 2021). This is based on G20 countries with well-developed infrastructures. Poorer countries of the global south have more work to do in developing infrastructure. Circular economy provides the opportunity for global south economies to put in place infrastructure with significantly less negative impacts on environment and resource depletion. "In 2022, the buildings and construction sector accounted for 34% of all energy-related CO2 emissions. Global investment in the sector has risen almost 55% from $156bn in 2015 to $285bn in 2022" (Spencer 2023). To address inequality the necessary global investment in infrastructure in the global south must be even higher. To avoid an increasing impact on CO2 emissions, environmental degradation, and climate change a systemic approach to circular economy during infrastructure growth is needed.

Global sustainability and controllable climate change require an aggressive move toward a circular economy. International cooperation is essential. This requires a multinational focus on major global supply chains. In December 2023, the United Nations held its 28th Conference of the Parties (COP28) climate change conference. The series of COP summits is a notable international effort to address climate change and ecological sustainability. These international meetings have addressed energy and technology policies on a global scale that will impact efforts toward a circular economy. Large, developed nations dominate the global supply chain. Their policies have a significant impact on the supply chain operation of global south countries.

A nation's effective advancement toward a circular economy requires system thinking that accounts for the micro and macro level particularities. It also must consider the external impacts on the nation's production and distribution processes. Particular attention must be given to new mega-projects. These projects not only command a large part of national resources but also have a longer lifespan than older and smaller projects. Mega-projects also impact a wide range of related projects in place and planned for future development. Projects of this nature generally involve international contributions through technology transfer, financing, or multinational corporate involvement.

National planners need to understand the functionality and management of the supply chains related to the nation's productive processes. Technology policies must be put in place that align the strategic objectives of primary enterprises with government priorities. Project management techniques must be applied that account for supply chain dependencies and maximise the benefits of an evolving circular economy. The traditions of project management have evolved to provide a systemic slant to operating large-scale projects. The project management literature presents various approaches to staging projects. An examination of the variations in project management steps lead to identifying a staging designed to link supply chain constraints with circular economy realities. This effort draws on recent research in using a maturity model approach to assessing and guiding circular economy transformation.

METHODOLOGY

System thinking views the world as elements connected through spatial and temporal relationships. The system thinking methodology is employed in three steps: Linking elements by relationships, system dynamics, and Framework Construction. Details on each step are conveyed in Figure 1.

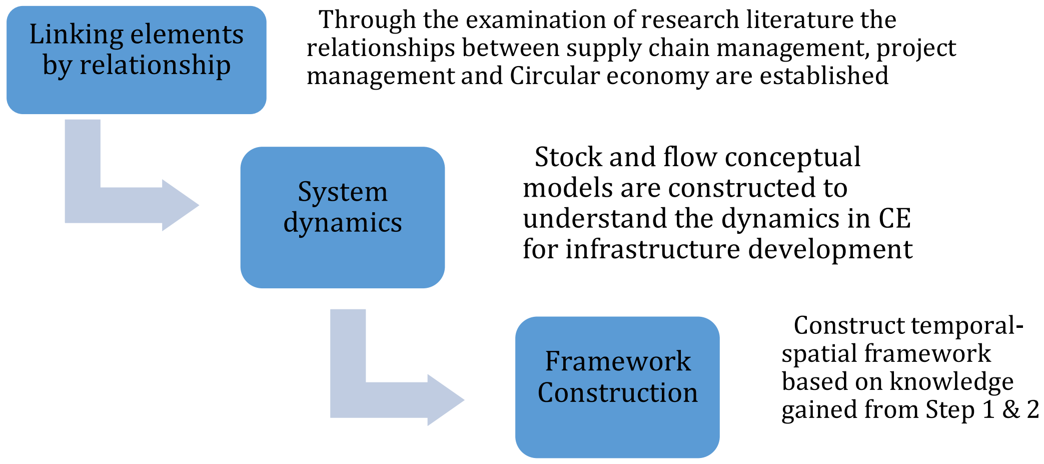

Figure 1. System Thinking Methodology

First, this paper seeks to link project management and supply chain management (SCM) with the advancement of circular economy (CE). Previous work on CE, SCM and project management provide the background for investigating best approaches to implementing CE in infrastructure development. Secondly, this paper uses the conceptual modelling capacity of system dynamics (Sterman 2000). System dynamics (SD), first utilised to examine industrial dynamics, applies nonlinear systems theory (Forrester 1961). In this study SD is used to construct a series of models that convey the relationship between SCM and CE. A series of conceptual models of infrastructure development are developed with increasing levels of detail. Insights from these models are used to construct an Infrastructure development CE Framework.

System dynamics starts with dynamic thinking. Cause and effect occur around us constantly. Central to dynamic thinking is identifying key variables called stocks and secondary variables, called flows, that directly cause key variables to change. When an outflow from one stock is an inflow to another it reflects a change in the state of a variable. Real systems are complex with numerous stocks and flows linked to form various feedback. In Figure 2 the first iteration shows construction material results in waste but then is recycled back as useful construction material. The second iteration is more realistic but still highly aggregated. Most material is used in construction and much of the scrap is unrecovered.

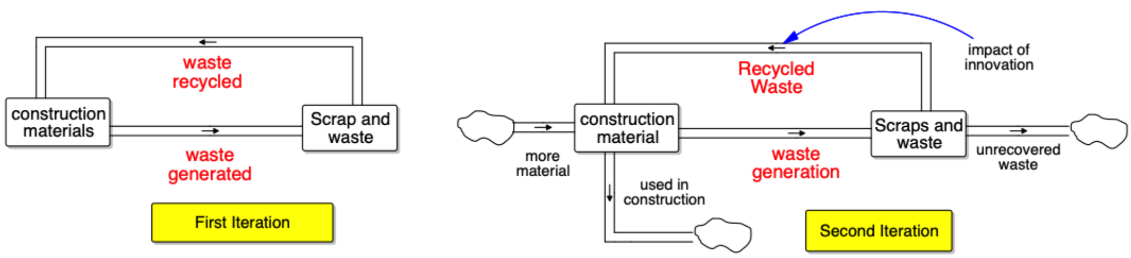

Figure 2. Two iterations of stock and flow process.

A tertiary variable 'impact of innovation' is included in the second model. Tertiary variables are constants or functions of stock and/or flow variables. More material is drawn from a 'cloud' that represents a source outside the model, while unrecovered waste flows into a cloud that is a sink outside the model. In this iteration 'impact of innovation' is a constant. Constants, sources, and sinks are system boundaries and reflect points of expansion for further iterations. These conceptual models are qualitative models that are used to engage stakeholders and lead to a better common understanding of the situation and future alternatives. When historical data is available these conceptual models can be quantified, and computer simulations conducted. The resulting patterns from these simulations provide insight into the future state of key variables. This study is limited to the use of qualitative SD models to identify key system variables. These SD modelling results aid in constructing a general-purpose framework for circular economy.

RESULTS & DISCUSSION

Linking Project management, supply chain management and circular economy

The Project Management Institute (PMI) defines a project as "a temporary endeavour undertaken to produce a unique product, service, or result." Table 1 displays a commonly used model of project management life cycle based on (Heagney 2012).

Table 1: Popular Project management Life cycle

CONCEPT	DEFINITION	PLANNING	EXECUTION	CLOSEOUT
Marketing Input *Survey of* *Competition*	*Define Problem.* *Develop Vision.* *Write Mission Statement*	*Develop Strategy.* *Implementation Planning.* *Risk Management*	*Do all Work.* *Monitor Progress.* *Corrective Action*	*Final Reports.* *Lessons-Learned* *Review*

Mauss, Bühner and Fottner, (2023) presents a change management approach to promoting the circular economy in the manufacturing sector. It is based on extensive literature review and semi-structured interviews of experts. Table 2 depicts their 3-Stage change management model. The model identifies change characteristics of three types: corporate realignment, systemic change, and ecosystem dependency. Shaping market conditions to help implement a comprehensive Circular Economy lies outside the purview of a single company or organisation. Industry, society, and politics significantly influence market conditions. This model and change management in general are faced with limitations in efforts to convert to a circular economy.

Table 2: Change management model for Circular Economy

Initiation Stage	Internalisation Stage	Implementation Stage
Raise internal awareness. Clarify the scope of CE, derive business benefits, illustrate potential threats	**Develop vision & strategy.** Formulate the vision holistically and strategy incrementally, identify low-hanging fruits, start with a single product/process	**Remove obstacles.** Ceteris paribus no longer applies, utilise CE champions as divisional facilitators, utilise low-hanging fruits as flagships
Gain vertical and horizontal commitment. Secure top management commitment, initiate cross-divisional collaboration, appoint and integrate CE champions	**Establish circular corporate culture.** Secure top management commitment, initiate cross-divisional collaboration, appoint and integrate CE champions	**Display progress.** Start to transform the business model, set measurable indicators, visualise and communicate achievements and benefits

Supply Chain Management

Technology complexity contributes to the significance of supply chain management. Infrastructure development has increased in intricacy and magnitude. The construction of Dams, electrical power stations, major highways and rail systems are larger, more complex, and more expensive than ever. Most of these major projects are government sponsored. However, they are implemented by a range of contractors and subcontractors. Often the infrastructure endeavour requires proposals, reviews and pilots before the actual project is initiated. These mega-projects engage a range of suppliers of parts, materials, and services in the supply chain. When state owned enterprises (SOEs) coordinate the development and operation of infrastructure projects, they can set policy and terms of operation for much of the supply chain. This allows mega-projects in general and infrastructure projects in particular to play the major role in a government orchestrated shift to a circular economy. This is particularly the case in the global south where infrastructure development lags that of developed countries. "Effective supply chain management involves the management of supply chain assets and product, information, and fund flows to grow the total supply chain surplus. … There is a close connection between the design and management of supply chain flows (product, information, and funds) and the success of a supply chain" (Chopra 2019, 18). Complex infrastructure projects are faced with supply chain management challenges due to the need to engage multiple industries. These multiple industries are concerned with sustainability as urbanisation increases the importance and size of infrastructure projects. This has led to work examining project management practices across Infrastructure supply chains (Xue et al 2018).

Circular Economy

The concept of circular economy (CE) is of great interest for manufacturing companies since it provides a framework which allows them to align organisational objectives with the Sustainable Development Goals (SDGs) (Diaz et. al. 2021). To create, preserve, and recover the value of assets and products, corporate CE requires the implementation of several value-retention choices (R-strategies) throughout an organisation's operations. The sustainable product development (SPD) process, in which around 80% of the total environmental impact of a product is determined, is employed to translate R-strategies into new product requirements (Diaz, et al. 2021). The production-consumption system that is made and controlled by people is embedded in the wider biophysical environment that, although not controlled by human activity, may be influenced thereby (Velenturf et al. 2019).

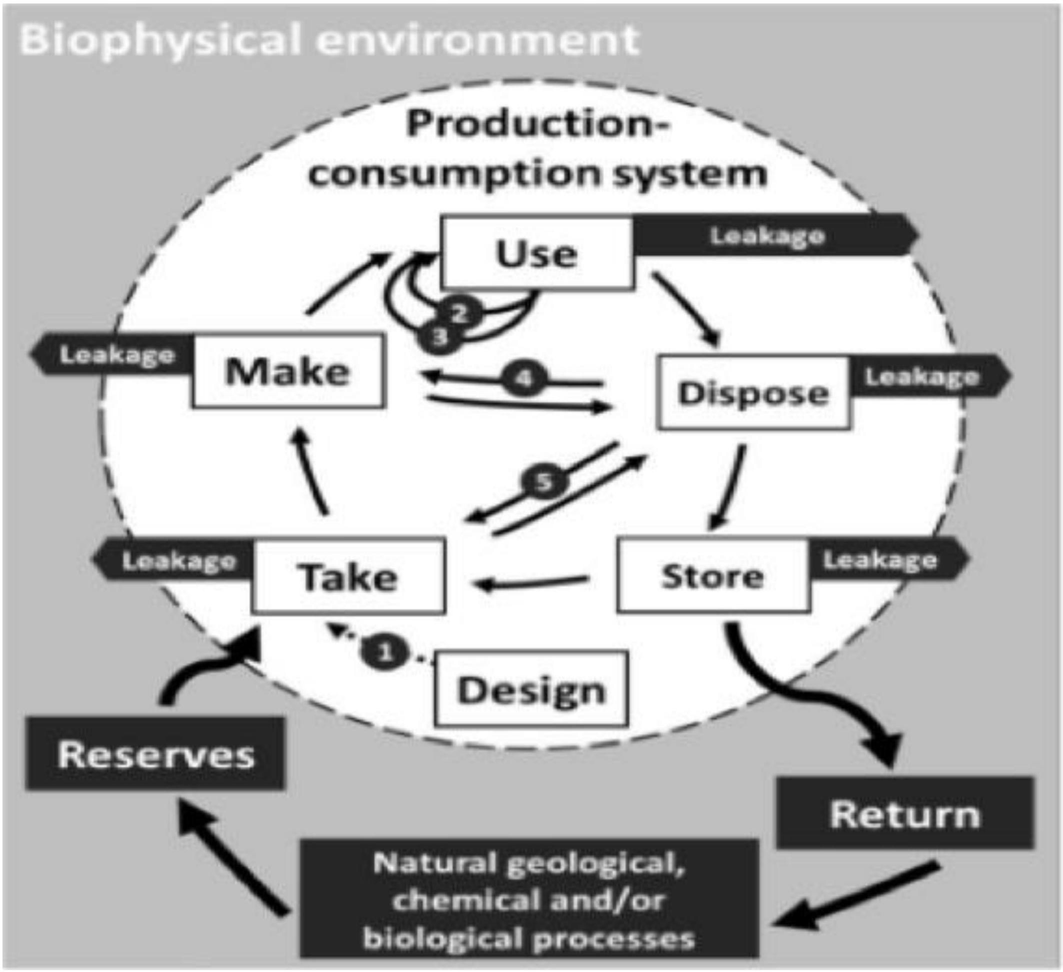

Figure 3. Integrated resource flow diagram for the circular economy (Velenturf et al. 2019)

(legend: Thick arrows are natural materials, thin arrows are industrial materials, dotted arrow is immaterial; [1] prevention by designing out all avoidable wastes, [2] shared consumption, [3] reuse and repair, [4] remanufacturing, [5] recycling).

Table 3: Project Management of Circular Economy (4 phases and 7 steps)
[table constructed from information in source (Kurzydłowska 2017, 546-549)]

Phase 1	*Step 1. Establishing scope and goals*	*Examples of parameters quantifying environmental impact: •the quantity of the raw material used, amount of local materials used, foreign materials required and expenses associated in delivery •amount of energy needed, •amount of the emissions to the environment. Scope is linked to •timing with the definition of the stages and the milestones, • List of assumptions and • Risks recognized*
Phase 2	*Step 2. Setting up the project execution team*	*The team consists of the representatives of all the stakeholders and assignment of duties. • Definition of roles & responsibilities of each project team member •Assignment of resources with appropriate qualifications to respective project tasks*
Phase 3	*Step 3. Preparation of the project execution plan*	*• Task planning, which break up project into subtasks; • Costs estimating; • Recognition of assumptions taken during planning activities; • Staffing – resource assignments; • Scheduling* *Best to involve the project team in the project scheduling.*
Phase 4 Implementation	*Step 4. Risk management*	*Project Risk Management steps: 1. Create prioritised list of risks* *2. Develop alternative mitigation actions, 3. Analyse mitigation actions and choose one that is preferable 4. Update project schedule & plan with all tasks arising from mitigation actions*
	Step 5. Change management	*Project change might influence: • Time (schedule) • Scope (requirements) • Costs. Treating changes in a project in a formal way assures: 1. That only truly needed chances are made,* *2. The consequences of each change are fully recognized, 3. The changes made are well communicated to all the stakeholders.*
	Step 6. Disseminate information (communication)	*Efficient communication plan developed in Step 3. It defines procedures in the context of to whom and what information must be forwarded. During the project implementation stage, project progress must be communicated to all stakeholders.*
	Step 7. Knowledge generation (lessons learned)	*Lessons learned should address: • Good and so good aspects of the project implementation • Areas of possible improvements.* *• The views of the Clients (stakeholders)*

Production-consumption systems should ideally be created with a sustainable circular economy in mind, giving special attention to the important product design phase. Throughout a product's whole existence, the design is perhaps responsible for 80% of its effects on the environment (Aldersgate Group, 2017). Infrastructure projects have a unique production-consumption situation since they focus on construction. Large infrastructure projects require the acquisition and transport of significant quantities of raw materials such as steel, concrete, glass and wood. The amount of materials sourced locally can have a considerable impact on the project.

Kurzydłowska, (2017) points out that project management generally acknowledges projects are subject to three constraints – scope, time, and cost. To address these constraints in moving toward a circular economy a seven-step approach is developed. This is summarised in Table 3 and is presented as four phases since the final four steps can be conducted concurrently. Uhrenholt, et al., (2023, 2) developed "a systems perspective in guiding organisations in their CE transformation using assessment tools—in this case a maturity model." This effort had three objectives: identify organisational dimensions of the circular economy; identify circular economy maturity levels from the microeconomic perspective and use a systems approach to propose a maturity model for the circular transformation for the manufacturing organisation.

The six dimensions of the organisation of circular economy are presented in Table 4 and the six levels of organisational maturity are captured in Table 5 (Uhrenholt, et al. 2023).

Table 4: Dimensions of circular economy (Uhrenholt, et al. 2023)

Dimension	Definition
Value Creation	The models utilised for generating and capturing value from CE activities (e.g., sales models, life-extending services) and environmentally positive performance (e.g., resource and emissions savings and regeneration).
Governance	The strategies and plans for the circular transformation (e.g., resource allocation, circular awareness, and different hierarchical engagement levels).
People and Skills	Mindset and skills (internal and with external partners) required to enable and act on CE transformation (circular competencies, learning, training culture).
Supply Chain and Partnership	The stakeholders external to the organisation required for the exchange and optimisation of materials, products, and activities (e.g., shared visions and activities, engagement with external experts).
Operations and Technology	The equipment and systems in place for performing CE activities (e.g., machinery and tools, systems aiding the scheduling and identification of appropriate treatment according to value potential).
Product and Material	The characteristics of the products that enable circular strategies and activities (e.g., extended life cycle, simple disassembly, and refurbishment).

Table 5: Levels of circular economy (Uhrenholt, et al. 2023)

Level	Definition
None	No presence of circular awareness, elements of circular economy in strategies, or related activities in the organisation. Only legal requirements are in place.
Basic	The need for CE appears in the organisation, and discussions about how and where to act are happening. Few, unintentional CE principles generate value.
Explorative	Demonstration projects and pilots are initiated across different functions in the organisation to prove the value of the CE and to test organisational capabilities.
Systematic	Means for pursuing CE are implemented, by design, throughout the organisation. Successful pilots are implemented, and scaling is initiated.
Integrative	Circular initiatives and ambitions are aligned throughout the organisation and its critical supply chain.
Regenerative	The organisation is truly engaged in the circular economy and is regenerative and restorative by intention and design.

'People and Skills' impact all the other dimensions. In this model 'Supply Chain and Partnership' is concerned with supply chain elements outside the primary operation that is addressed in 'Operations and Technology'. People engaged in circular economy transformation play different roles. This is why it is important to distinguish different stakeholder categories.

A textbook approach identifies project stakeholders in two categories. Internal stakeholders are top management, project team members, your manager, peers, resource manager and internal customers. External stakeholders are external customers, government, contractors, subcontractors, and suppliers (Watt 2014). Insisting that stakeholders address the circular economy is critical in any organised effort to bring about change. Trimble and Muchie, (2024) categorise stakeholders in groups: 1) educational institutions; 2) government structures; 3) international agencies; 4) non-governmental organisations (NGOs), non-profit organisations (NPOs), and community organisations; 5) the private sector; and 6) engaged citizens. Regarding the Appropriate Technology Manifesto, each group has different interests and must be approached in particular ways to elicit support for the appropriate technology agenda. When organising meta-projects, the government and organising team can use this categorization to elicit external stakeholder support. Advancing CE requires implementing appropriate technologies through all phases of project management and all points in the supply chain.

Stakeholders' impact on the different logistical supply chain drivers must be guided to eliminating waste and CO_2 emissions, while making concrete moves toward a circular economy.

Maturity models

Organisations use maturity models to determine how well they are conducting business or developing a product. The Capability maturity model (CMM) for software development was established by the Software Engineering Institute (SEI) at Carnegie Mellon University in 1987 and became a widely used tool to access software organisations (Paulk, et al. 1994). The concept of maturity models has extended to address the implementation of circular economy (CE) and used a similar five level analysis starting with 'none' and reaching the highest level of regenerative. This is a particularly useful tool as a high-level approach to the circular economy taken on by state agencies at a national level. State agencies planning for a circular economy on a national level should find this CE maturity model useful. Understanding the current level of CE is an important starting point for any project seeking to improve the circular economy. The maturity assessment can be made on the macro level and determine the national readiness for CE. The assessment can also be made on a micro level and determine the level of CE for suppliers, sub-contractors, and other participants in the project supply chain.

Employing System Dynamics

Funding is key to infrastructure development as well as transitioning to CE. This is indicated in Figure 4 with the three highlighted Funds variables. Funds for infrastructure construction CE are an addition to funds for new infrastructure when using a traditional linear economy. This model aggregates damage done by linear economy to construction waste and infrastructure operation waste. This conceptual model can be quantified by selecting a particular project or sector and identifying the waste products. One example would be to quantify waste in terms of CO_2 emissions. In this model infrastructure has been disaggregated into construction and operation phases. However, the model has aggregated the various stages of the supply chains associated with construction and operation.

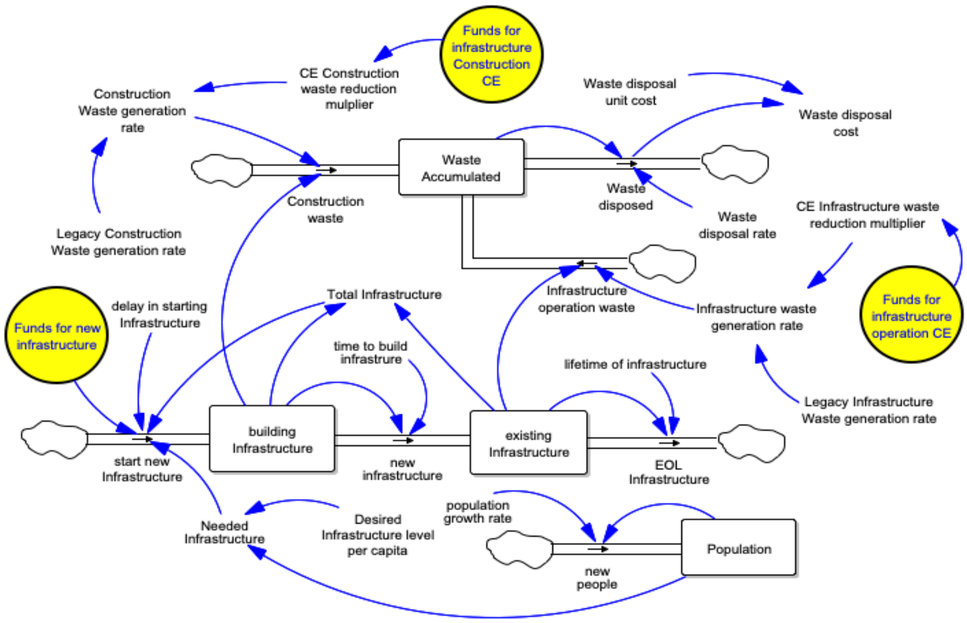

Figure 4. Implementing Circular Economy in Infrastructure Construction and Operation

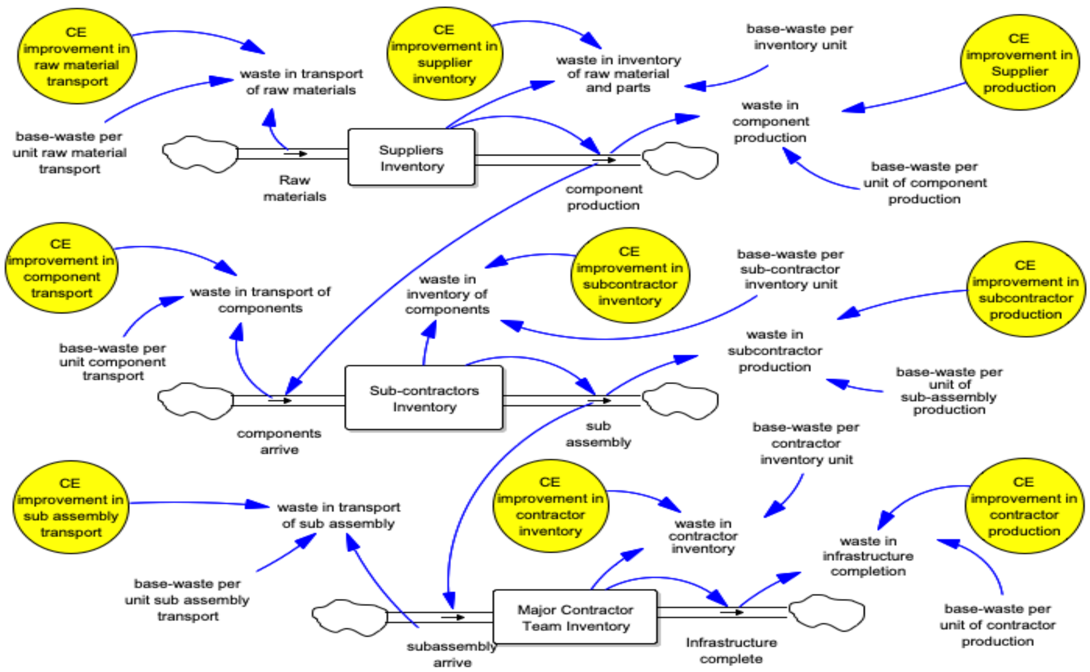

Figure 5. CE improvement in three level supply chain of Infrastructure Construction

Figure 5 focuses on infrastructure construction. Suppliers convert raw materials into components that are transported to subcontractors responsible for sub-assemblies that are transported on to the major contractor. This final contractor's production results in completion of the planned infrastructure. This three-level model is simplified for illustrative purposes. It serves as a template for the project management team. In real world environments it is possible for suppliers to transport components directly to the final contractor. Also, it is possible to have suppliers sending components to other suppliers and subcontractors sending sub-assemblies to other sub-contractors. Each stage in the supply chain addresses CE improvement for the supply chain drivers - facilities, inventory, and transportation. Improvements associated with production correspond to the facilities location and operation. The series of stock and flow diagrams provide stakeholders with the fundamental dynamics engaged in infrastructure construction and operation. The identification of the nine points for CE improvement in Figure 6 is key to constructing the comprehensive CE framework. The core of the framework lies in tailoring the steps in project management consistent with CE in infrastructure development.

CONCLUSIONS

The system thinking approach resulted in the five stage CE framework displayed in Figure 6.

Each of the five stages from investigation through closure is concerned with CE along two dimensions – supply chain nodes and supply chain drivers.

For each node in the supply chain, CE is considered as that node links to other nodes in the supply chain network. This network linkage forms the first dimension. Of particular interest in this linkage is transportation and how CE strategies address transport of inputs to the SC node and outputs from that node. Optimising transport has always been a concern of SCM.

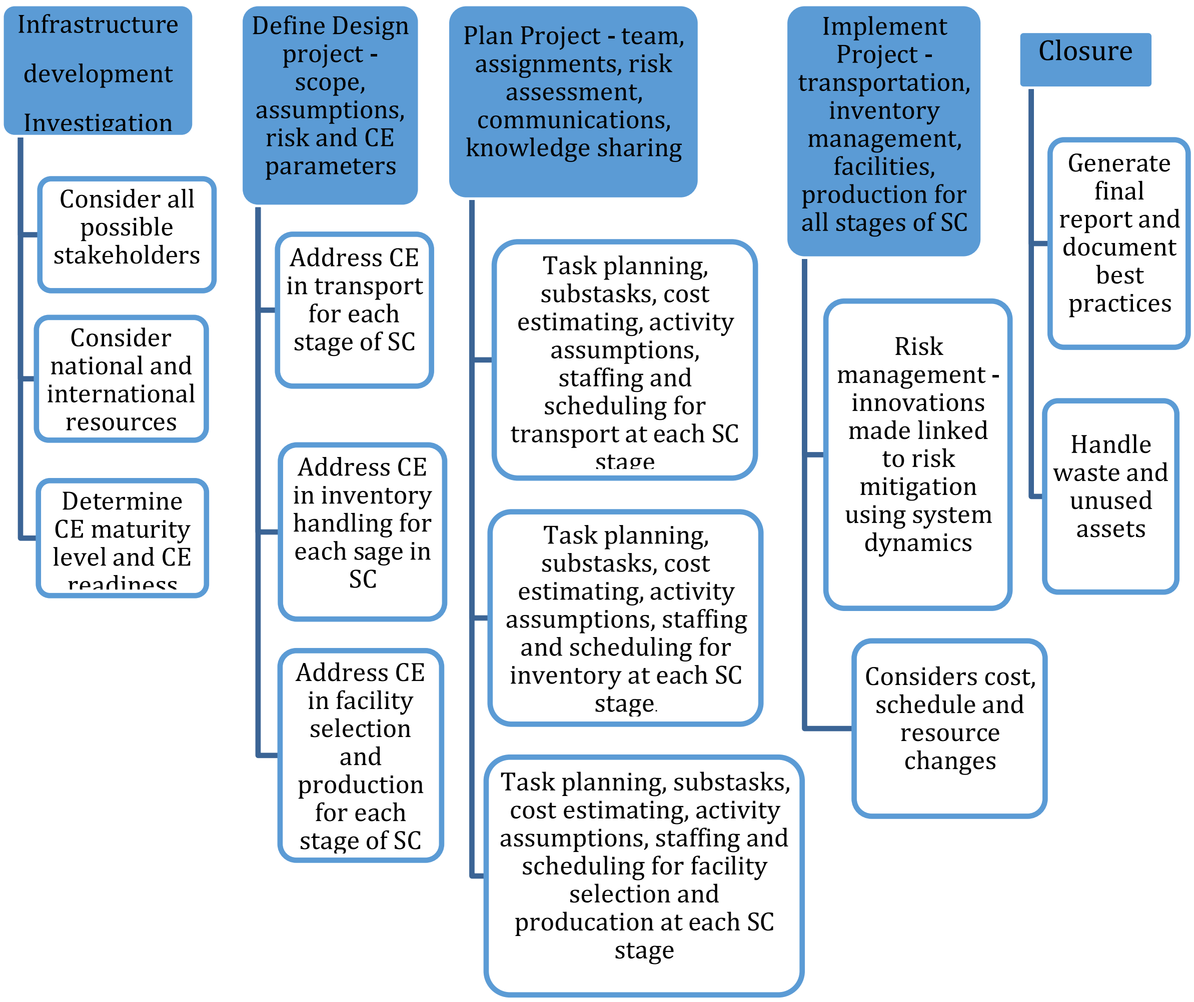

Figure 6. Project Management Framework for a Circular Economy

The drive to CE motivates projects to optimise waste in transport and consider CE in the life of transport vehicles. Transport is only part of the SC drivers that form the second dimension. Inventory management and facility location and operation are also elements of this second dimension. For each node in the supply chain, the CE associated with each of these SC drivers must be addressed.

Project Investigation

Before a decision is made to start an infrastructure project, a comprehensive investigation of the situation is necessary. All potential stakeholders are identified, and various scenarios are examined to consider the different roles they may play. Infrastructure projects can have both national and international implications that must be considered. An example is the building of the Grand Ethiopian Renaissance Dam (GERD). Before initiating this project, a range of discussions, studies and decisions had to be made engaging both Egypt and Sudan. In many cases infrastructure projects may depend on international funding and technology transfer. Most governments have rigorous guidelines for infrastructure projects that involve alternative proposals, public hearings, formal bidding for contracts and sub-contracts. Infrastructure projects must focus on the control cost related to material purchase and construction. This requires precise estimation and cost control (Shah et al, 2023). This stage identifies all government requirements and restrictions. This investigative stage also considers the long- and short-range implications of involvement of international agencies, other governments as well as multinational corporations. As indicated earlier, infrastructure project development and infrastructure operation contribute significantly to CO_2 emissions and other environment changes. It is important that this investigation determine the CE maturity level of the situation. Based on the potential scope of the project this may involve local, national, or regional investigation. In addition to the current level of CE maturity, a measure of CE readiness should also be established. How prepared the potential project participants are to advance the CE maturity status is a factor in the success of the project.

Project Definition

This stage starts with the project management components traditionally associated with this stage. Considering all aspects of the investigation, project scope, goals, objectives, and stakeholders are determined. Setting the project scope and goals determine the government requirements related to infrastructure development. All assumptions are clearly laid out as well as constraints and potential risk. Recognizing the supply chain structure of the project is essential for a clear project definition. This is a complex responsibility since at this stage the suppliers and subcontractors usually have not been fixed. The CE parameters are determined at this stage. Stock and flow models such as Figure 5 are expanded to define these CE parameters most effectively. They are defined for potential suppliers, sub-contractors as well as the main contractor. Information sharing among stakeholders is essential to effectively set CE parameters. These parameters address CE advancement for facilities, inventory, and transportation (the three logistical supply chain drivers).

Project Planning

Planning the project focuses on setting the team and making clear assignments for all team members. A clear line of accountability and reporting must be established at this point. This stage includes plans for risk assessment, communication and knowledge sharing that can be used throughout the project. Task planning takes place at this stage. For the different points in the supply chain the project is divided into subtasks. Cost estimating is performed for all subtasks. Recognition of the impact of assumptions is considered during planning activities. Staff and resource assignments are made for all tasks and subtasks. The CE strategies associated with the identified CE parameters are placed in the context of the different stages of the supply chain and the context of the logistical supply chain drivers. CE is considered for all subtasks associated with facility location and operation, transport between facilities and the inventory handling of all materials, components and sub-assemblies associated with the project. These CE strategies consider the selection of materials and methods, production alternatives and handling of waste from each subtask. Infusing innovation in these CE strategies is key in preparing an effective project plan.

Project Implementation

This stage handles transportation, inventory management, facility planning and production for all stages of the supply chain in the process of infrastructure construction. Risk management is a critical part of ongoing project implementation. It drives project change. All project change is linked to risk mitigation, and considers cost, schedule, and resource changes. System dynamic models are quantified with alternative scenarios to share risk options with shareholders. This is used to plan effective risk mitigation. Communication and Knowledge generation during project operation are linked. Sharing information among suppliers, subcontractors and contractors across the SC facilitates best practices and maximising benefits while minimising costs across the SC. Emphasis is given to the implementation of tasks and subtasks associated with the various CE strategies. As project milestones are reached assessment of CE gains are made. The change management process addresses adjustments to CE strategy as needed. Information from risk mitigation and change management contribute to the knowledge base on CE best practices associated with the tasks and subtasks of the project.

Closure

How the knowledge base is preserved and presented to stakeholders is an important aspect of project closure. This framework is to address building infrastructure not the continued maintenance or operation of the infrastructure. The project ends with completion of the infrastructure construction. The final step of project implementation is to address all waste and asset disposal associated with project completion. This must be done for all nodes in the supply chain of the project. The closure report should include a reassessment of the CE maturity level.

Multi-step system thinking leads to this robust project management approach to CE-focused infrastructure development. The framework starts and ends with application of the CE maturity model. The two dimensions employed in project management facilitate infusion of CE innovation for the different components in the supply chain, at different stages of project management. The conceptual models developed using system dynamics can be extended during the stages of project management to communicate the dynamics of the situation and assist in attaining a shared vision of the CE process in infrastructure development. This framework is a synthesis of supply chain management, system dynamics and project management techniques applied to infrastructure development projects. It requires the user to determine CE parameters and appropriate CE innovations and strategies.

FUTURE WORK

Careful evaluation of infrastructure construction can supply additional data and parameters for the stock and flow model leading to a quantitative system dynamics model used to simulate alternative scenarios. This is useful in risk assessment during the project planning and implementation stages of project management. Future work will focus on developing quantitative models in conjunction with the use of this framework and continue investigating the role of the different stakeholder groups and how use of system dynamics models can provide clarity on the critical nature of CE. Project constraints, such as resource limitations, government regulations, and competing projects make up the project external environment determining the conditions for change that must be considered when applying the framework. The system dynamics methodology is used to identify the relationships among the contending forces impacted by infrastructure development. This can be used to present alternative scenarios regarding the extent of CE implementation. These scenarios will provide a better understanding of the demands that must be made of the different stakeholders engaged in infrastructure development and operation, as well as the limitation the external environment places on CE implementation. The comprehensive review process of our original paper allowed for the identification of an additional future research agenda item. The unique nature of infrastructure projects' emphasis on construction requires a closer examination of materials used and the transport processes associated with their acquisition.

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MITIGATING CLIMATE CHANGE AND RURAL POVERTY: ETHICAL, SUSTAINABLE GLOBAL ECOVILLAGE NETWORKS

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ABSTRACT

A consortium of sustainable, ethical ecovillages can challenge catastrophic climate change and rural poverty by replacing top-down international development models with more effective bottom-up replacements. In this paper we propose a truly global consortium of ethical, sustainable ecovillages. We describe an ethical framework suitable for deliberations by global consortium members on the consortium's ethical principles. We present examples of African and Indian ecovillages demonstrating this model's integration of ethics and action. Numerous existing ecovillages operate with no awareness of the existence of other ecovillages and no mechanism for sharing their experience and best practices with their peers. The conclusion first describes India's success in creating clusters of thousands of ecovillages on the PURA model of Professor A.J.P. Abdul Kalam, former head of the Indian space agency and president of India from 2002 to 2007. We then propose establishing a web-based portal to assist network members with ethical deliberation and sharing best practices in ecovillage development..

Keywords climate change; rural poverty; ethical ecovillages; international development; JP Abdul Kalam

INTRODUCTION

Numerous linked problems need to be addressed to achieve sustainable development worldwide, such as mitigating the impacts of climate change and poverty in both rural and urban areas (Sachs et al., 2019). To help societies achieve sustainable development, connected and organized efforts are needed along scale from the local to the global (Kates et al., 2001). Implementing western scientific knowledge and technology globally in targeted initiatives has proven an excellent approach to help diverse communities move towards achieving sustainable development. However, engaging local stakeholders and expertise in a collaborative process has the best chance of moving scientific knowledge and technology into action at the community level (Cash et al., 2003).

Local micro-conditions must be considered when seeking to design and implement knowledge and technology for sustainable development. What works well in one village, may not in another, even if it is just down the road (Meinzen-Dick, 2007; Ostrom et al., 2007). As Fonseca and others report in these pages, “Looking into ecovillages as laboratories of innovations and social technologies for sustainability, developing and testing solutions adaptable to each territorial context at the microscale of the communities open up a range of new possibilities that may be appropriated by the broader debate on building more sustainable futures” (Fonseca et al. 2022, 5; (4). A bottom-up approach in which the solutions to problems are locally developed is often more effective than a top-down approach through governance and policy (Fraser et al., 2006; Ostrom et al., 2007).

Over the last decades a variety of bottom-up approaches have been tested to determine how they can empower local communities to help them achieve sustainable development (Schwab & Roysen 2022). In this area of study, both university and non-governmental based collaborative learning networks are proving useful. They combine the real time agility and local specificity needed to meet the challenges of implementing knowledge and technology at the community level. Examples include coastal fisheries, the Arctic and ecovillage networks (Alexander et al., 2015; Armitage et al., 2009; Berkes & Armitage, 2010; Fazey et al., 2020); Amar, 2023; Bluesmith, 2023).

One of the keys to success that research with the networks has revealed is the integration of non-local and local knowledge. In this so-called boundary work, non-local knowledge must be woven across differences of local cultures, values, attitudes, and worldviews. A collaborative merger must synthesize local community perspectives, expertise, and experiences to ensure that knowledge and technology implementation are optimized (Clark et al., 2016; Goodrich et al., 2020; McGreavy et al., 2013).

However, researchers are now questioning the ethics of these transfers using boundary work networks (Armitage et al., 2009; Bamzai-Dodson et al., 2023; Nadasdy, 1999; Wilmer et al., 2021). They have recognized that knowledge and technology transfer, if one-sided, can amount to further westernization and imperialization. Change of local community culture during knowledge and technology transfer may be unavoidable to some degree but allowing the transfer process to remain unfettered full-scale so that it leads to disempowerment and dilution of the local culture is unethical.

In this paper, we propose what we see as two critical next steps in the continuing evolution of global boundary work for sustainable development. First, we propose that all ecovillage networks across the world include deliberation on ethical platforms in their collaboration processes. We support our proposals for ethical deliberation by global consortium members and access to their contributions to ethical, sustainable development worldwide, by presenting our research on exemplary ecovillage networks in Africa and India (Tharakan, 2015a, 2015b; Verharen et al., 2021; Verharen et al., 2019; Verharen et al., 2014; Verharen et al., 2013).

Second, we propose establishing a truly global consortium of ecovillages, both rural and urban, based on a web portal. Although GEN with ten thousand members is the most comprehensive consortium, our research discloses numerous ecovillages that are not in its network (Oliver, 2017; Miller, 2018). The portal will enable global access to best practices in ecovillage development. Our recent research in Africa and India demonstrated that numerous ecovillages operate in isolation, often with no awareness of the existence of other ecovillages and usually with no mechanism for sharing their experience and best practices with their peers.[1] A critical function of the portal will be to form a global coalition of ecovillages that can amplify the efforts of figures like Saleemul Huq to call attention to the Global North's responsibility to fund climate mitigation in the South. Particularly important is Huq's injunction that funding be guided by locally led adaptation. He has helped inspire the movement from top-down to bottom-up international development (Huq et al., 2018; Adger, 2006).

Schwab and Roysen in these pages advocate "translocal networks" that help community-led initiatives like ecovillages to "engage with national and transnational actors, to lobby transnational governments and to build alliances with other social actors" (Schwab & Roysen 2022, 2; Loorbach et al., 2020). A primary purpose of the proposed global portal is to foster the growth and lobbying power of such translocal networks. Avelino and others provide "an empirical analysis of translocal networks that work with social innovation both at the global and local level" that includes GEN as a case study (Avelino et al., 2020, 1).

In the results section of the paper we present a synopsis of dominant African, Asian and European ethical systems. Our objective is to counter a Eurocentric concentration on deontological, utilitarian and virtue ethics in order to provide members of a global consortium

[1] An earlier version of the paper was published electronically in *Proceedings of The 10th International Conference on Appropriate Technology* (Verharen et al. 2022). Brief sections of the paper on global ethics and African ecovillages were published in journals in different contexts intended for different audiences (Verharen 2021, Verharen et al. 2021).

of ecovillages with a framework for deliberation on the consortium's ethical principles (Pascual et al., 2023; Caniglia et al., 2023; Ling, 2023; Verharen et al., 2021; Verharen et al, 2014). Current ecovillage consortia such as the Global Ecovillage Network (GEN) and the Foundation for Intentional Communities (FIC) are not grounded in explicit ethical principles that unite their members. Somewhat surprisingly, the global ranking systems for sustainable development such as Leadership In Energy And Environmental Design (LEED), Building Research Establishment Environmental Assessment Methodology (BREEAM), and Green Business Certification Inc. (GBCI) also do not ground their judgments in ethical principles. The irony is that the professionals responsible for designing and executing sustainable projects are guided by the ethics adopted by their professions. Ranking systems would benefit from similar guidelines.

The discussion section presents the results of research carried out for one month in Benin in November, 2018 and two weeks in India in November, 2022. Our team visited four Songhaï ecovillages in Benin and four ashrams and a health center in remote areas of India. Through chain referrals and social networks, we engaged in deep collaborative discussions with community leaders and members, attended community meetings and lectures, and conducted informal, unstructured, and non-directive interviews. We accompanied community members on their daily tasks, including on-site visits to remote communities struggling with poverty. We also collected archival data that included reports, pamphlets, and instructional literature.[2]

METHOD

Our literature review on ethical, sustainable development in agroecological villages in the essay's primary areas included the following sources. Research in education for global sustainability shows promise for developing a consortium of ecovillages (Adenle et al., 2015; Barlett & Chase, 2013; Bennett et al., 2018; Kates & Dasgupta, 2007; Lotz-Sisitka, Belliethathan, et al., 2017; Lotz-Sisitka & Shumba, et al., 2017; Matiwaza & Boodhoo, 2020). Research connects environmental ethics and sustainability (Fernandes & Guiomar, 2016) with emphasis on agroecological villages in Africa (Bellwood-Howard & Ripoll, 2020; Brombin, 2019; Gliessman, 2018; Miller, 2018; Mousseau, 2015; Nicholls & Altieri, 2018; Pimbert, 2017; Xue, 2014). Critical to a global consortium of ecovillages is development of information communication technology, particularly in Africa's poorest regions (Asonguab et al., 2018; Oladipo & Grobler, 2020; Tchamyoua et al., 2019; Wei, 2020). The following sources define an *ecovillage* as a deliberately designed and focused rural or urban enclave committed to sustainability, poverty elimination, public health and education through the use of appropriate technologies (Fonseca et al., 2022; Koduvayur Venkitaraman, 2022; Schwab, 2022; Singh et al, 2019; Brombin, 2019; Miller, 2018; Xue, 2014; Adenle et al., 2015).
Given a limited period to conduct fieldwork, we used a series of rapid appraisal and assessment methods.

We conducted an intensive period of fieldwork over a month in Benin in November 2018 and over two weeks in India in November 2022, with additional information collected prior to and after that period. The dates of our fieldwork are as follows: Songhaï Center, 11/17-

[2] No datasets were generated or analyzed during the current study.

12/19/2018; Muni Seva Ashram, 11/3-6/2022; SEARCH, 11/7-9/2022; Anandwan, 11/9/2022; Art of Living, 11/10-11/2022; Auroville, 11/12-14/2022.

RESULTS

The Evolution of Ethics

In this section we present a brief synopsis of seven values that African, Asian and European cultures have deployed over the past five thousand years (Fernandes & Guiomar, 2016). The summary is presented here as a stimulus for a global consortium of ecovillages to reimagine a system of ethics powerful enough to confront contemporary existential crises such as global climate change, the sixth mass extinction, weapons of mass destruction, global state or group terrorism, and global pandemics. Members of a global consortium should include research on indigenous ethical systems that have escaped the influence of dominant global systems in their deliberations on ethics.

The oldest recorded ethics emerging in ancient Egypt some five thousand years ago recognizes the fact that values enter into competition with one another. A community's task is to harmonize that conflict in order to guarantee life's continuity. The Egyptian ethical value, called *Maat,* is variously translated as harmony, peace, justice, truth in different contexts in the *Book of the Dead* (Faulkner, 2005/1972, Assmann, 1996, Hornung, 1990/1982, 1999/1995, 2001/1999), Verharen et al., 2014).

The second oldest ethics are found in Hinduism, Buddhism and Daoism emerging some 2400 years ago. The overarching value in these three traditions is the control of attention through meditation. That value is subservient to higher values such as awakening to one's own divinity (Hinduism), eliminating suffering (Buddhism) or harmonizing complementary forces (Daoism). Nevertheless, meditation in all three systems is the only secure path to those goals. The wisdom of these traditions is that conscious, rational direction of attention is more likely to promote survival than allowing accidental direction as a function of environmental circumstance (Koller, 2016).

At roughly the same time as the emergence of Asian ethics, Greek philosophers promoted reason as a unique human attribute deserving to be regarded as a paramount value. Reason is defined as the ability to abstract patterns from the vast multitude of experience. The generality of the patterns permits the prediction and control of experience. Both Plato and Aristotle believe that the most fortunate humans would dedicate their entire lives to the pursuit of reason (Plato, 1966; Aristotle, 1941).

Around two thousand years ago, Christ in West Asia singled out love as the paramount value. His definition of love was provocative in that it commanded a universal human community bound together by universal, unconditional love. While earlier philosophers in Africa and Asia advocated a single human community, Christ was the first to make love the paramount value.

Distinctively European ethics emerged during the time of the 18th and 19th century industrial revolutions in Western Europe. Like earlier African and Asian philosophers, John Stuart Mill emphasized ethical obligation extending to a universal human community. Perhaps emboldened by science and technology's growing power to enable the control of experience, Mill insisted on human ethical obligation to sentient creatures capable of experiencing pleasure and pain. Mill designated pleasure, happiness or well-being as the foundational value (Mill, 2014/1859).

While not an ethicist in any conventional sense of the term, Darwin called attention to perhaps the most salient point about ethics through his research. After confirming the constant extinction of species, Darwin reminds us that survival is the precondition for any concern about the best possible definitions of flourishing (Darwin, 1936/1859/1871). Unless survival can be assured, speculation about the best possible ways to live is otiose (Verharen et al., 2013, 2014).

And finally three 18th and 19th century German philosophers have enshrined freedom as the value that now controls the world in the form of globalization. Kant defines freedom as human activity controlled by the iron first of reason (Kant, 2017/1797). Hegel provides a definition of freedom as “the infinite capacity of activity to change its form” (Hegel, 1956/1837, p. 206). Marx defines political freedom as the absence of constraint by an authoritarian government (Marx & Engels, 2002/1848).

Deliberation on a global ethics for ranking a global consortium of ecovillages should take advantage of these five thousand years of wisdom. As said above, this wisdom must be supplemented by research into indigenous ethics that have escaped the influence of dominant cultures. Particularly important for constructing a global system of ethics is dialogue with members of communities working on new formulas for ethics.

Discussion

An African Network as Ecovillage Exemplar

Professor Godfrey Nzamujo, a Nigerian Dominican priest with a background in philosophy, theology, microbiology, computer systems and international development, started a system of rural African ecovillages in Porto Novo, Benin, that serves as an exemplar model for a global network of ecovillages (Nzamujo, 2002). The villages feature appropriate technologies that enable green energy production, “cradle to cradle” recycling of other resources, agroecological food production including post-harvest processing for value addition, primary health care, and education from pre-school through post-secondary levels as well as on-site training and workshops including a Songhai Leadership Academy designed to develop coming generations of innovators (Bellwood-Howard & Ripoll, 2020; Lotz-Sisitka et al., 2017; Nicholls & Altieri, 2018; Mousseau, 2015). Nzamujo named the villages Songhaï Centers in honor of a fifteenth century West African empire.

Nzamujo grounds his Centers in three ethical principles: autochthony, autonomy and authenticity. He defines *autochthony* as a principle of rooting a village in the physical and cultural “soil” of the over fifty centers in seventeen African countries. The villages enrich their soil through organic fertilizer produced in the villages and forbid the use of chemical pesticides. Drip irrigation conserve scarce water resources and cross-planting controls for pests. Processing organic waste enables closed-loop systems that promote sustainability (Nzamujo, Personal Communication, 15/05/2020).

Nzamujo’s second ethical principle of autonomy permits the villages to be self-sustaining, once the extensive capital costs for land, structures, Information Communication Technologies (ICT), biological labs, and other start-up costs are covered. Revolutions in the ethics of ICT distribution in the form of Massive Open Online Courses (MOOCs), open access publishing, and decreasing costs of international broadband access permit the extensive educational system that is key to ecovillage autonomy (Asonguab et al., 2018; Barlett et al., 2013; Lotz-Sisitka et al., 2017 Oladipo & Grobler, 2020; Tchamyoua et al., 2019).

Nzamujo’s third ethical principle is authenticity. He defines this term as Songhaï community responsibility for the survival and flourishing not only of community members, but of community neighbors to the degree possible. Nzamujo has created the Songhaï Leadership Academy to make it possible for interested parties from around the world to stay at the Songhaï Center in Porto Novo to learn how to set up ecovillages on the Songhaï model in their own areas (Nzamujo, Personal Communication, 15/05/2020).

Indian Rural Ashrams, Health Centers As Ecovillage Exemplars

Gandhi’s call for India’s escape from British enslavement and colonization presages Nzamjo’s three ethical principles of autochthony, autonomy and authenticity. The Indian independence movement featured local resources and indigenous technologies such as the spinning wheel that became emblematic of the cause (Singh et al., 2019). The authors' recent research in India disclosed examples of ashrams and health centers that embody the ethical values presented in the results section and Songhaï Centers above.

EXAMPLE 1. A dramatic example is the Muni Seva ashram near Vadodara in Gujerat that dedicates itself to health care with a 400-bed hospital specializing in cancer care. Schooling includes pre-kindergarten through college levels as well as vocational education with an emphasis on nursing. The ashram includes education for girls and women regardless of caste or economic class

EXAMPLE 2: SEARCH (Society for Education, Action and Research in Community Health) in Gadchirolli at the eastern end of Mahrashtra is a health-focused ecovillage that is situated in the tribal area of the Gond Forest. Established by Drs. Abhay and Rani Bang, SEARCH aims to address the almost complete lack of access that tribal communities have to reliable primary health care. Their model engages with the tribal communities to determine their health care priorities, giving voice to the tribal women in making that judgment. SEARCH has developed a model for reducing infant mortality not simply in its Gadchiroli base but throughout India and 12 other countries (R. Bang et al., 2011; A. Bang, 2016).

The ethos of SEARCH is to work with the people. As Dr. Abhay Bang has articulated, the power shift from top-down to bottom-up is a transformation from research *on* the people to research *for* the people to research *with* the people and ultimately research *by* the people (A. Bang, 2010).

EXAMPLE 3: Anandwan styles itself as a SMART village located in the Chandrapur district of Maharashtra. The acronym SMART stands for Sustainable, Measurable, Affordable, Replicable and Technologically Advanced. Baba Amte inaugurated Anandwan in 1949 in order to provide marginalized people with excellent lives. While initially focused on dealing with the scourge of leprosy in India, Anandwan has branched out from leprosy care to develop schools, training centers, workshops and manufacturing facilities for the blind, deaf persons and persons with disabilities. The village is moving toward energy independence with the installation of concentrated solar power units and photovoltaic grids.

EXAMPLE 4: Additional collective Indian ashrams called "The Art of Living" consist of communities that set up service projects around the world.

EXAMPLE 5: One of the best-known ecovillages grounded in meditation in India is Auroville, founded by Mirra Alfassa, known as "The Mother," under the influence of Sri Aurobindo in 1968. Like other ecovillages, Auroville focuses on alternative energy systems.

CONCLUSION

1.An Indian Inspiration for a Global Ecovillage Network Portal

Professor A.P.J. Abdul Kalam, the former head of the Indian space program who became president of India between 2002 and 2007, has written *Target 3 Billion: PURA—Innovative Solutions Towards Sustainable Development.* The book articulates a demonstrable path to global poverty's elimination. His acronym, PURA, stands for "providing urban amenities to rural areas." The book features examples of clusters of ecovillages in rural areas that provide virtually all the features of urban life to rural communities. Kalam argues that 7,000 PURA complexes in India would eliminate rural Indian poverty and that 30,000 PURA complexes would end global rural poverty and promote a dramatic reduction of global migration (Kline et al., 2020). While such numbers may seem preposterous, Kalam envisions the PURA villages as consortia of numerous villages compounded into a dynamic whole.

The PURA Village Cluster comprises "a group of villages sharing basic economic and social assets, such as connecting roads, markets, advanced health-care services, higher educational facilities and electronic connectivity" (Kalam & Singh, 2011, 32). Sizes range from 10 to 50 villages. PURA clusters "emphasize agro-processing, develop local crafts, dairy farming, fishing and silk production so that non-farm revenue for this sector is enhanced, based on the core competency of the region." Kalam offers working examples of the PURA concept in present day India.

2.Constructing A Global Ecovillage Network Portal

Our research on Indian ashrams and health centers reported above shows that few examples know of Abdul Kalam's work with PURA and none of the reported examples know of the successes of their fellow ashrams or health centers. Consequently we propose initiating a global web portal of ashrams, rural health centers, and ecovillages that allows members to exchange information about their solutions to their problems, their successes and failures. The global consortium would also offer its members the opportunity to compare their results with those of their peers by means of ethical checklists created consensually by its members.

We propose a twofold approach to establishing the global web portal. The first step contacts existing ecovillage consortia such as GEN and FIC as well as the ecovillages, ashrams and health center cited above to determine their interest in establishing the portal to help expand their outreach.

The second step proposes the establishment of the Howard University Center for Ethical Global Sustainability (HUCEGS) that will house a global web portal that will link to exemplars of successful ethical ecovillages including the Songhai Center, Muni Seva Ashram, SEARCH and Auroville. HUCEGS will develop a roster of successful ethical, sustainable ecovillages operating in diverse geographical, environmental and socio-political realms. HUCEGS will serve multiple functions, with a primary focus on the ability of community members to exchange information about their successes and failures in solving their problems. In addition to serving as a global repository for information and links to ethical ecovillages, HUCEGS will work as a global network consortium that would offer its members the opportunity to create a consensual ethical checklist to help compare their efforts to those of their peers.

Finally, the portal will develop and offer programs along the lines of the SEARCH Nirman program to select and train the next generation of changemakers and ecovillage founders. Featuring the Nirman initiative on the portal is critical to the global expansion of ecovillages.

We are currently applying for an NSF ethics in STEM grant to assist the HUCEGS start-up and are now contacting GEN, FIC and our research partners in Africa and India to assess their interest in setting up the global portal. The NSF program is the Ethical and Responsible Research Program with submission in January 2024 (Program No. 23-630, https://new.nsf.gov/funding/opportunities/ethical-responsible-research-er2).

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SECTION: ENERGY & MATERIALS

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AFRICANS' CONTRIBUTION TO THE PROGRESS OF 100% RENEWABLE ENERGY

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ABSTRACT

In both urban and rural areas, having a reliable power supply connected to the grid is crucial for success. Solar, wind, and hydro are the three primary renewable energy sources utilized to produce electricity in Africa. The report assesses the current state of the power industry and proposes a plan of action for African countries to adopt to incorporate these three renewable energy sources. A model for integrating renewable energy sources for secure, sustainable, and cost-efficient energy is anticipated to bridge the energy gap. The high cost of renewable energy poses a barrier to large-scale projects. Constructing large-scale energy self-sufficiency initiatives at affordable prices will be achieved through community involvement in appropriate technology initiatives and ample incentives.

Keywords: Africa, Sustainable, renewable energy, prosperity, collective finance,

INTRODUCTION

Allen(Allen 2020) emphasized the significance of energy as the primary pillar of prosperity, with the economy being the second. Energy is utilized as a representation of prosperity due to the interconnectedness of economic activity and energy consumption. When analyzed on a country-by-country basis, GDP per capita and per capita energy consumption display a strong correlation (Ourworldindata.org 2024). Even in scenarios where industry and consumers exhibit enhanced fuel efficiency in response to elevated fuel costs, the relationship persists, more or less universally. Electricity is recognized as the ultimate output of various energy forms, and with the advent of electric vehicles, alternative modes of transportation, modern household appliances, and telecommunications, electricity will continue to symbolize prosperity. Electricity has evolved into an essential prerequisite for bolstering economic endeavors and elevating the overall quality of human life. The current status of national electricity access among populations is depicted in Figure 1, with certain nations achieving full coverage. This study envisions a future where Africa will possess a nearly unified electricity grid. By harnessing the abundant renewable energy resources within the continent, Africa has managed to double its renewable energy output between the years 2012 and 2021, (IRENA The International Renewable Energy Agency 2022), more could be done through evolving the people in financing such projects as an appropriate technology for development. Some key words mainly used in this paper are interchangeable: Energy with electricity; and Renewable energy with hydro, solar, and wind.

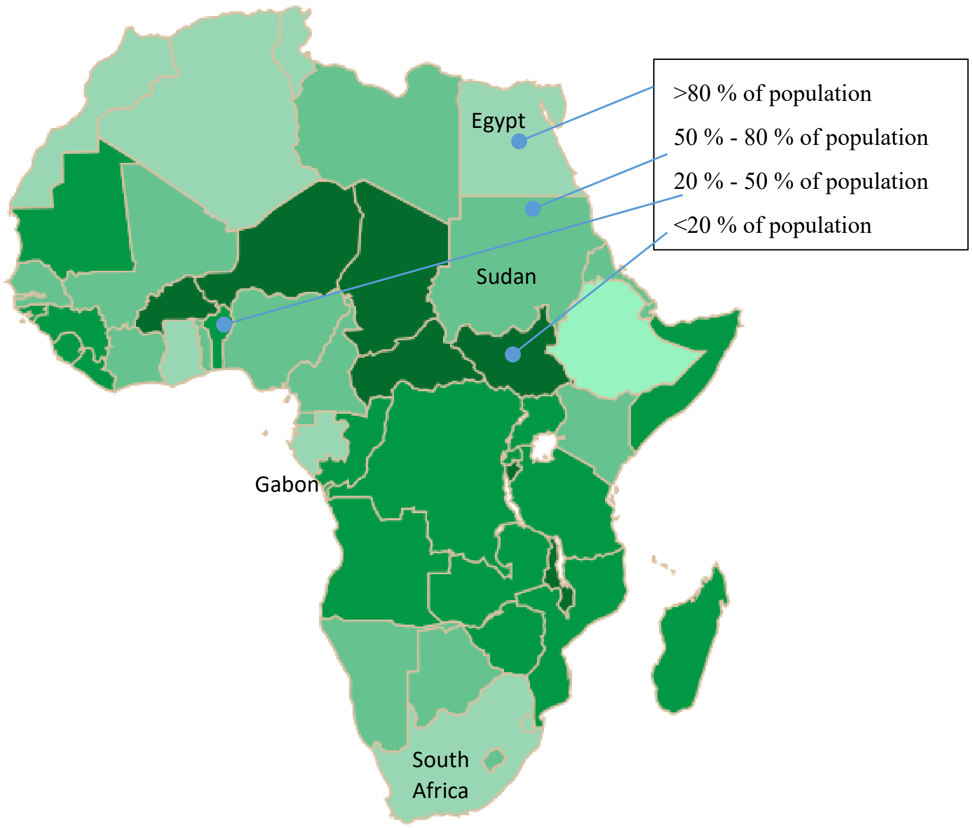

Figure 1: *Africa* Population access to electricity-National (% of population) (The African Development Bank 2021)

Associated Research

Thermal power plants are an important part of the energy mix and are essential for supplying the increasing demand for electricity in many African nations. These plants supply a steady and dependable supply of electricity, which is necessary for economic expansion, the advancement of industry, and raising living standards. However, producing thermal electricity in Africa is not without its difficulties. Burning fossil fuels like coal and oil can contribute to air pollution and greenhouse gas emissions, which is one of the main causes for concern. Concerns about fuel source price and availability also exist, as does the requirement for infrastructure and technological investments in order to increase efficiency and lower emissions. In spite of these difficulties, thermal electricity generation continues to be an important part of Africa's energy sector. Many countries are exploring cleaner alternatives such as natural gas and renewable energy sources like solar, wind, geothermal and biomass power, (IRENA The International Renewable Energy Agency 2022) to diversify their energy mix and reduce their environmental impact.

Renewable energy in Africa is gaining momentum as countries on the continent seek to reduce their reliance on fossil fuels and mitigate the impacts of climate change. Several African countries have abundant renewable energy resources, including solar, wind, hydro, and geothermal power, making them well-positioned to transition to a more sustainable energy future. From (IRENA The International Renewable Energy Agency 2022) statistics Africa renewable energy share is less than the world share; and developing in slower rate than the rest of the world; Table 1. South Arica and Egypt are the main players in renewable as Sudan and Ethiopia in the hydro electricity production; Table 2, (IRENA The International Renewable Energy Agency 2022).

Table 1: Renewable energy share of electricity capacity

%	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
World	26.2	27.3	28.3	29.6	30.8	32.1	33.2	34.6	36.6	38.3
Africa	18.8	19	19.6	20.1	20.1	21.2	21.7	21.8	22.6	23.1

Table 2: Division of Total and Renewable Electricity Installed Capacity and Africa Rank (#) in five African Countries (Gigawatts GW)

Countries	Total capacity	#	RE capacity	#	Hydro capacity	#	Solar capacity	#	Wind *capac*ity	#
South Africa	63.28	1	10.13	1	0.69	17	6.22	1	2.96	1
Egypt	60.07	2	6.27	2	2.88	3	1.68	2	1.64	2
Ethiopia	4.9	10	4.76	3	4.07	1	0.02	26	0.32	5
Gabon	0.78	25	0.33	25	0.33	21	0	47	0	27
Sudan	4.47	11	2.26	10	1.92	8	0.14	9	0	47
All Africa	244.64		56.05		34.96		11.15		7.33	

Hydropower has historically served as a major electricity provider in Africa, as numerous nations have depended on extensive dam systems for power generation (see Table 3). Nevertheless, there is an increasing focus on smaller hydro projects that can supply power to isolated communities without requiring substantial infrastructure investments.

Solar power shows great potential in Africa, with numerous nations allocating resources to develop extensive solar energy initiatives aimed at supplying electricity to isolated regions and lessening dependence on costly and environmentally harmful diesel generators. Furthermore, smaller solar systems are being implemented to deliver off-grid electricity to rural communities lacking access to the primary power network, as highlighted by Onsa's analysis; (Mahmoud H. Onsa and Iman 2022). Utility scale solar farms are now found in many countries; South Africa had the largest solar energy capacity in Africa as of 2022, reaching over six gigawatts (GW). Egypt recorded the second biggest capacity, at 1.7 GW, see Table 2. Sudan started by a 5MW, (M.H. Onsa and Hassan Modwi 2023).

Table 3: Top 10 Hydroelectric Power Plants in Africa

#	Hydro Electric Plant, Country	Time	Power (MW)
1	Grand Ethiopian Renaissance Dam (GERD), Ethiopia	started in 2011	6,450
2	Aswan, High Dam, Egypt	1971	2,100
3	Cahora Basa Dam, Mozambique	1969-1979	2,070
4	Gilgel Gibe III Dam, Ethiopia	2006-2016	1,870
5	Inga Dams, Democratic Republic of the Congo	1972-1982	1,775
6	The Kariba Dam, Zambia / Zimbabwe	1955-1959	1,626
7	Merowe Dam, Sudan	2009	1,250
8	Tekeze Dam, Ethiopia	2009	1,200
9	Akosombo Dam, Ghana	1961-1965	1,020
10	Kainji Dam, Nigeria	1968	760
	Total Africa capacity		34,960

(Ethiopian Business Review 2023),(Mwangi Alberto 2023), (Cozzi and et al. 2022).

Wind power is also gaining traction in Africa, with several countries investing in wind farms to harness the continent's strong winds. Ethiopia, Kenya, Morocco, and South Africa are among the leaders in wind energy development on the continent. Table 4 provides some details of the largest wind farms there are wide financing; the largest is 310MW and the Africa total is 7,830 MW.

Table 4: The Largest Wind Energy Projects in Africa (2023)

#	Wind Energy Project		Date	Country	MW
1	Lake Turkana Wind Farm	Private investment to date, valued at $650 million.		Kenya	310
2	Tarfaya Wind Farm	$560-million Private/	2015	Morocco	301
3	Ras Ghareb Wind Farm	$400-million Engie (40%), Toyota-Tsusho/Eurus Energy (40%) and Orascom (20%)	2016 2019	Egypt	263
4	West Bakr Wind Project	$320-million Lekela Power, private and government incentives	2021	Egypt	250
5	Adama I & Ii Wind Farm	830 GW government	2021	Ethiopia	204
6	Akhfenir Wind Farm	Moroccan Wind Energy (EEM)	2016 2023	Morocco	250
7	Taiba N'diaye Wind Farm	US$161 million export loan facility	2021.	Senegal	158
8	Kangnas Wind Farm	140MW consortium of international IPPs and financiers.	2018 2020	South Africa	140
9	Khobab & Loeriesfon -Tein 2 Wind Farms	2*140MW	2017	South Africa	140
10	Boulenouar Wind Farm	100 MW, $167-million by the Spanish Elecnor SA and the German Siemens Gamesa.	2022	Mauritania	120
	Total capacity				2086
	Africa total capacity				**7830**

(Energy Capital and Power 2021)**,** (Cozzi and et al. 2022)**.**

Geothermal energy is another promising renewable resource in Africa, particularly in East African countries, north eastern Africa (Kenya and Ethiopia, Egypt and Red Sea), and northern Africa. These countries have significant geothermal potential and are investing in developing this resource for electricity generation. (Merem et al. 2019), (Elbarbary et al. 2022). Biomass energy is one of the renewable sources. It demonstrates the biolocical products, of animal or plant origin, used to alter the biological chemical energy to heat energy and then to electrical energy. Biomass has a big role, especially in rural areas of Africa. It is not used in mega-electricity production yet, (Dasappa 2011), (Wiranarongkorn et al. 2021).

Overall, renewable energy has the potential to transform Africa's energy landscape by providing clean and reliable electricity while also creating jobs and stimulating economic growth. However, challenges such as financing, infrastructure development, and policy frameworks need to be addressed to fully realize this potential. Nonetheless, African governments and international organizations are increasingly recognizing the importance of renewable energy and are taking steps to support its development across the continent.

The integration of renewable energy sources and the production of electricity from sustainable sources are the main concern of this paper requires an effective common African network will ensure a steady supply of electricity, (Bird, Milligan, and Lew 2013). Ensuring adequate substation and distribution capacity for the end customers is one of the many duties included in power system distribution network planning, or PSDNP. A well-designed distribution network is advantageous to both urban and rural residents, (Hammons et al. 2000), (Irechukwu, Irechukwu, and Mushakangoma 2021). The network must be interconnected due to variations in weather patterns, power sources, and consumption patterns. Thermal electricity generation in Africa is a significant source of power for many countries on the continent. This method of electricity generation involves using heat to produce steam, which then drives turbines to generate electricity. The heat can be produced from various sources, including coal, natural gas, or oil. Table 1 gives the total and renewable electricity capacity in Africa, the thermal energy mostly 75% is the difference between the total and the renewables.

MATERIALS AND METHOD

Current situation of electricity situation

The current situation of electricity in African countries was shown in the above section; indicates that African has a lot to do to declare a 100% renewable continent within a decade. The previous information stated above and the huge material that is raised in the mentioned references; together with other internet sites form a solid material for the situation. RE is one the technologies that need to be managed within the appropriate technology frame work for the prosperity, sustainability of the African communities.

Benefit of Integration of Renewable Energies

Hydro-energy can be considered as energy storage to cater for the fluctuation of solar and wind energies. With the characteristic of quick start-stop of hydro and the advent of electronic communication and control this becomes the norm of using hydro as a backup source, (Bird, Milligan, and Lew 2013). The Hydro-energy integration will lead to higher penetrations of solar and wind energies. Stefan Ambec and Claude Crampes; (Ambec and Crampes 2012) examined the relationship between a consistent source of electricity generation and sporadic sources like solar or wind energy.

Financing African Renewable Energy Projects

Investing in renewable energy in Africa can offer attractive returns while also contributing to sustainable development and environmental protection. Investing in renewable energy in Africa can be a good investment for several reasons: Growing demand due to increase of population and their standard of living; together with having abundant renewable energy resources. Environmental benefits; through reducing the greenhouse gas emissions compared to fossil fuels, investing in renewable energy can contribute to a cleaner and healthier environment for the people of Africa. Investing in renewable energy can create jobs, stimulate economic growth, and attract foreign investment to the region. It can also help reduce reliance on imported fossil fuels, improving energy security and reducing vulnerability to price fluctuations; and after all will create economic and political stability.

Methods of financing renewable energy projects: in Africa can be through a number of ways, such as:

1. Development financing institutions (DFIs): DFIs including the World Bank, International Financing Corporation, and African Development Bank finance and assist with technical aspects of renewable energy projects in Africa.

2. Commercial banks: In Africa, commercial banks are allowed to finance renewable energy projects through debt. They might provide working capital loans, project finance loans, or other forms of funding.

3. Impact investors: These are individual investors who aim to achieve both financial gains and social and environmental benefits. They might finance African renewable energy initiatives with debt or equity.

4. Crowdfunding: A lot of individual investors can contribute money to renewable energy projects in Africa by using crowdfunding platforms.

5. Public-private partnerships (PPPs): PPPs are a means of developing and financing renewable energy projects in Africa through cooperation between the public and private sectors. By doing so, you can pool resources from both industries and share risks.

6. Green bonds: Green bonds are fixed-income securities that are used to raise funds for environmentally friendly projects, including renewable energy projects in Africa.

7. Grants and subsidies: To promote renewable energy projects in Africa, governments, international organizations, and non-governmental organizations may offer grants or subsidies.

8. Carbon credits: Greenhouse gas emissions from renewable energy projects may be credited toward the production of carbon credits, which may be sold on the carbon market to bring in extra money.

Africa offers a wide range of financing alternatives for renewable energy projects, each having pros and downsides of their own. It is imperative that project developers thoroughly assess their financial requirements and investigate the various funding options at their disposal. All things are to be considered; and to have a new dimension to appropriate technology; a utility scale power plant can be constructed involving the mass, crowd or a lot of individual investors bonds such as green ponds.

RESULTS AND DISCUSSION

Examples of renewable energy financed Projects

Table 5: Some African financing methods for renewable energy

Project	Year	Country	Financer
High Dam	1961	Egypt	World Bank, Then The Soviet Union
Tarfaya Wind Farm	2015	Morocco	$560-million Private
Bui Dam	2013	Ghana	China
Grand Ethiopian Renaissance Dam,GERD	2011-	Ethiopia	Donations and government bonds.
Kairouan 100-Megawatt Solar Farm	2023	Tunisia	$86 million, multi-donor fund, private sector, African Development Bank, Sustainable Energy Fund for Africa (SEFA)
Noor Ouarzazate Solar Complex	2020	Morocco	The World Bank

Overall, these projects demonstrate the World Bank's commitment to supporting some renewable energy development in Africa and helping countries transition towards a more sustainable energy future. Private sector and donation can make a real supporter. Large power plants are always developed and operated by the governments, but private sector plays a good role.

Solar PV and wind energy projects have a great return nowadays. While the real cost of electricity in the majority of African countries is \$0.12/kWh, there are offers for as little as \$0.03/kWh of renewables. The private sectors need transparent regulations and bylaws as well as economic stability. This can be accomplished by offering market research and feasibility studies together with support access to technological data, market share, and economic and technical risk assessments.

The African Model of Renewable Energy Integration

The three main renewable energies mentioned above can be modelled to give sustainable grid, moreover the African countries can work together to provide a stable, reliable and sustainable grid. Solar systems use solar energy for generating electricity normally using PV modules; this is totally depending of the availability of sun light by day time. Wind systems use wind turbines for generating electricity from wind power, this is obviously depend on availability of wind at suitable speeds. Hydroelectric systems generate electricity from hydropower stored behind dams; built across rivers or pumped storage systems, or using tidal or wave energy. The various energy sources, their specific characteristics, and the 24-hour integration are modelled in Figure 2.

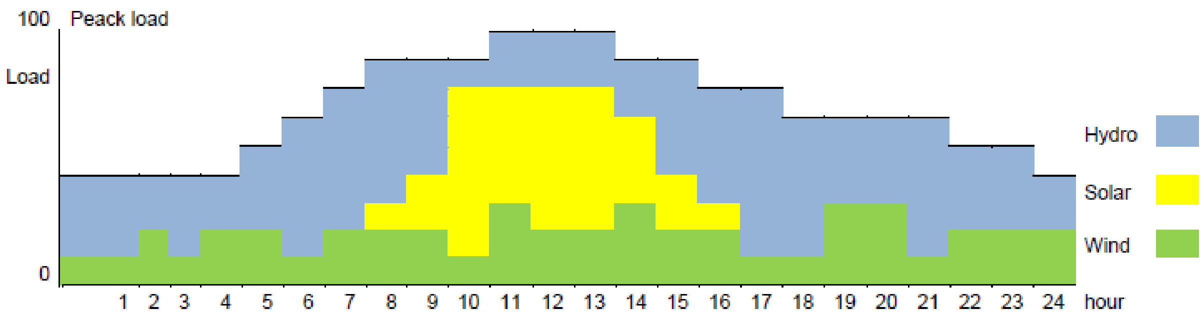

Figure 2: Model of the daily renewable electricity integration.

The process of integrating renewable energy sources into the electrical grid is known as renewable integration. Because power supplies are intermittent, a wind-solar combination can only offer a steady power source if electric batteries pack is employed to store energy. Due to their short lifespan, batteries are an expensive alternative both in terms of initial cost and running expenses. Hydroelectricity fills the gaps in the grid. From Tables 1-4 we see that Africa has a quite good renewable energy projects scattered all around the continent. The one or interconnected electricity grids will serve for integrity. The intended use of hydroelectric power is to act as a form of security for the benefit of all countries. A network comprising massive hydropower facilities with solar and wind electricity across Ethiopia, Sudan, and Egypt is a basic illustration of integration. Eretria, South Sudan, and Chad may be included to this network initially, and subsequently it will be expanded to become a component of the pan-African network.

CONCLUSION

Nowadays, having access to electricity is essential to boosting economic activity and raising living standards. Renewable energy resources in Africa are abundant enough to power the entire continent with a single integrated grid within ten years. To create a unified, reliable electrical infrastructure, Africa must technologically unite.

Whenever there is a disparity between supply and demand in a nation, utility-scale solar and wind energy projects ought to be implemented.

Hydroelectric power is intended to serve as a backup for the good of all nations.

In Africa, national grid connections have recently inaugurated, e.g. connecting Ethiopia, Sudan, and Egypt.

Instead of building or purchasing small self-sufficient renewable energy devices, financial bonds or certificates will serve as a suitable or appropriate technological instrument and provide a reliable and sustainable current for a country, and then for the entire continent. These days, solar photovoltaic and wind energy projects have excellent returns with short payback periods, as little as $0.03/kWh and 3 years, respectively.

RECOMMENDATION

Research is to be directed towards the integration of African to finance new renewable energy projects and electrical grids, and to how commercial and governmental institutions should sponsor green energy bonds.

The national banks and financial institutions should think about issuing financial bonds or certificates (green bonds) to finance utility-scale renewable energy projects instead of constructing or buying small self-sufficient devices, which are direct appropriate technologies. These can act as a suitable technological instrument and provide a consistent current for the entire nation.

To arrive at a shared platform for 100% renewable energy, the integrity of renewable in Africa needs to be discussed within African economic and financial institutions, such as the African Central Bank (ACB), the African Monetary Fund (AMF), the African Investment Bank (AIB), and the Pan-African Stock Exchange (PASE).

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SYNTHESIS AND PHYSICOCHEMICAL PROPERTIES OF ZINC-METAL-ORGANIC FRAMEWORKS-74 SUITABLE FOR CARBON DIOXIDE CAPTURE

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ABSTRACT:
Due to the increasing anthropogenic carbon dioxide (CO_2) emissions resulting in global warming, several technologies have been identified and implemented to reduce these emissions, including carbon capture, utilization, and storage (CCUS). Carbon capture through the application of metal-organic frameworks (MOFs) is one of the most promising approaches due to their unique properties such as high porosity, surface area, crystallinity, stability, and selectivity, and their vast number of applications including gas separation and gas storage. This study aimed to synthesize a novel Zn-MOF-74 material at various reaction temperatures and time using the solvothermal technique and determining its physicochemical properties to evaluate its suitability for selectively capturing CO_2 from flue gas produced by typical coal-fired power plants. The MOF crystals were synthesized at 100, 110, and 125°C over periods of 8, 12, 24, and 48 hours. The physical properties were evaluated through the Brunauer–Emmett–Teller (BET) analysis, while the surface chemistry, crystallinity, and morphology were probed using the universal attenuated total reflection Fourier Transform Infrared spectroscopy (UATR-FTIR), X-Ray Diffraction (XRD), and Scanning Electron Microscope (SEM), respectively. FTIR results showed the presence of carboxyl (C=O) and hydroxyl (-OH) functional groups which are crucial for CO_2 adsorption. The TGA results showed that samples synthesized at 48 hours and 125°C were the most thermally stable up to temperatures of 430°C. The synthesized materials exhibited surface area ranging from 1 to 55 m^2/g at different temperatures, with pore diameter ranges of 2.0 to 7.2 nm, respectively. Thus, the crystalline materials' physicochemical characteristics, which were produced at high temperatures and for 24 hours or less, indicated that they might be used effectively as a carbon capture material. It is recommended to evaluate the behaviour, effect of impurities, and performance of the MOFs during CO_2 capture using a synthetic flue gas.

Keywords: Anthropogenic carbon dioxide, Carbon capture, Solvothermal technique, CO_2 adsorption, Metal-Organic-Frameworks (MOFs).

INTRODUCTION

The growing demand for energy, transportation, and water treatment caused an increase emission of greenhouse gases with carbon dioxide (CO_2) being the most prominent emitted into the atmosphere. These emissions have resulted in significant environmental challenges, most notably global warming, and climate change. CO_2 emissions are caused mostly by anthropogenic activities such as fossil fuel combustion and transportation (Allangawi et al., 2023).

The International Energy Agency (IEA, 2022) mentioned that energy generation through coal-fired power plants has been the greatest contributor to CO_2 emissions. It is approximated that 80% of greenhouse gas (GHG) emissions in South Africa are from the energy sector. Thus, the country must transition away from coal to fulfil its Nationally Determined Contributions (NDCs) following the approved Paris Agreement (Hanto et al., 2022). During this transition, the CO_2 emissions need to be reduced from the atmosphere to meet the climate targets (IEA, 2022). Surridge et al. (2021) alluded that Carbon Capture, Utilization, and Storage (CCUS) has been identified as one of the technologies to minimize CO_2 emissions and as one of the

Nationally Appropriate Mitigation Actions (NAMA) of South Africa as outlined by the United Nations Framework Convention on Climate Change (UNFCCC). The CCUS technologies are critical for accessible, low-carbon electricity, with CCUS-equipped coal and gas plants producing 5% of global power by 2040.

South Africa (SA) has identified CCUS as one of the technologies to reduce CO_2 emissions. The country demonstrated carbon capture and utilization (CCU) technologies at the Kelvin Power Station in Kempton Park on March 20, 2024. This technology was funded by the Department of Science and Innovation (DSI) Hydrogen Society Roadmap for South Africa. As part of the country's commitment to climate change mitigation and carbon emissions reduction, the program intends to decarbonize hard-to-abate businesses, decreasing emissions while preserving and generating employment (Department of Science and Innovation, 2024).

Carbon capture efforts have resulted in an urgent need of creation of novel classes of porous materials with distinct applications in CO_2 capturing and sequestration. Metal-organic frameworks (MOFs) are one of the most promising adsorbents and have been recognized for gas separation and storage applications. MOFs are a class of porous crystalline materials composed of a regular array of metal ions connected by organic linker molecules forming a matrix that would be occupied by gas molecules. These materials have gained attention due to their promising properties, which include high porosity, surface area, and adsorption capacity, tuneable pore size and structure, more effective biodegradability and biocompatibility, and simplicity of functionalization (Ahmadi et al., 2022).

The MOF materials can function as storage containers with a sponge-like capacity for adsorbing and storing greenhouse gases. When a solvent molecule is removed, an unsaturated open metal site is formed which functions as a binding site for CO_2 molecules. This allows CO_2 molecules to adhere to the pore surface through dipole–quadrupole interactions which have a significant effect on CO_2 selectivity as well as the binding energy between adsorbed molecules and the surface of MOF sorbents (Raptopoulou, 2021).

According to Norouzbahari et al. (2023) rigidly constituted MOFs keep their open metal sites open to gas molecules. Zinc (II) cations with five coordinates are present at the borders of one-dimensional hexagonal channels in Zn-MOF-74. With its stable structure, oxygen-rich interior pore, coordination-unsaturated sites, and stable framework, Zn-MOF-74 is regarded as one of the most cost-effective MOFs. Zn-MOF-74 is a honeycomb-like material with pores of approximately 12 nm in size. The framework is composed of divalent metal ions and 2,5-dihydroxyterephthalic acid. Each metal ion has three O atoms from the carboxylate linker and two from the two 2-OH groups (Vrtovec et al., 2023).

One of the main challenges in considering the real functioning uptakes and identifying any potential constraints is the lack of knowledge regarding the effect of synthesis conditions on the physicochemical properties and performance of MOFs under real flue gas circumstances. Further enhancements and improvements in the synthesis of Zn-MOF-74 which result in physicochemical properties that are applicable for CO_2 capture under real-world flue gas circumstances should be performed. As such, it is necessary to do more exploration in the experimental synthesis conditions of Zn-MOF-74 using solvothermal technique, this includes the effect of different reaction temperatures and time on the physicochemical properties desirable for CO_2 capture.
The study was aimed at synthesizing Zn-MOF-74 suitable for selective post-combustion CO_2 capture with an effort to fundamentally contribute to the body of science including the efforts

to mitigate CO_2 emissions produced by coal-fired power stations. This was achieved by synthesizing Zn-MOF-74 samples while varying the synthesis temperature of 100, 110, and 125°C over periods of 8, 12, 24, and 48 hours, and characterization using Brunauer-Emmett-Teller (BET), UATR – Fourier Transform Infrared (FTIR), scanning electron microscopy (SEM), X-ray Powder Diffraction (XRD) to determine their physicochemical characteristics.

RELATED STUDIES

A study reported by Rehman et al. (2022), several techniques for producing MOFs in bulk quantities at a faster rate were described. It was discovered that the selection of metal ion source and organic linker enabled the synthesis of novel molecules. The adsorption capacity of CO_2 increased with increasing surface area and pore volume at high pressure. It was possible to increase the CO_2 adsorption capacity and stabilize the MOF by introducing functionality into the cavities of MOFs, specifically under wet conditions.

In a recent study by Aniruddha et al. (2020), a comprehensive evaluation of various MOFs utilized for carbon capture was conducted. The solvothermal approach was determined to be the most successful synthesis method. According to the kinetics, MOF adsorption primarily followed pseudo-second-order processes, either in conjunction with Toth isotherm or modified Langmuir isotherms. Moisture affinity, active sites and crystallinity were discovered to be important parameters to consider when screening the suitable MOFs.

The synthesis of MOF-74 involves a two-step solvothermal method, which includes the coordination of organic ligands and metal ions in a solvent at a suitable temperature and autogenous pressure and involves the reaction of an organic solvent and reaction material under high-temperature pressure hydrothermal to generate crystals (Gu, 2021).

The Zn-MOF-74 was first reported to be synthesized with other thirteen new MOFs (named MOF-69A-C and MOF-70-80) by Rosi et al., in 2005. 2,5-dihydroxy-1,4-benzenedicarboxylic acid (H2-DHBDC) and zinc nitrate tetrahydrate, $Zn(NO_3)_2 \cdot 4(H2O)$ were dissolved in N, N-dimethylformamide (DMF), 2-propanol and water, and placed in a Pyrex tube which was then frozen, evacuated, flame-sealed, and heated and then cooled to produce yellow needle crystals of MOF-74 (Xiao & Liu, 2019).

The reaction temperature and time have a significant impact on the creation and structure of MOFs, including ligand conformation, coordination mode, and transformation; metal center coordination ability; architectural topology, dimensionality, and structural transformation, among other things. The assembly, formation, and structure of MOFs can vary widely depending on temperature and other reaction circumstances, making it challenging to forecast and regulate the resulting MOFs (Xuan et al., 2018).

METHODS AND MATERIALS

Materials

The materials were purchased from Merck Group, Axiom, Protea Laboratory Solutions (Pty) Ltd, and Glass World. These materials were Reagent Grade (RG) and were utilized without additional purification. They were used for the synthesis and structural formulation of the Zn-based MOF-74 samples.

Synthesis of Zn-MOF-74

Solvothermal synthesis is an effective method to producing MOFs due to its simplicity and capacity to create a wide range of nanoparticles with a relatively small size distribution. It requires three main components that include an organic ligand, a metal salt, and solvent (Ingsel & Gupta, 2022). This approach provides for improved control over the form, size, and crystallinity distributions and has been used to generate nanoparticles and nanorods with and without surfactants (Kumari et al., 2023).

In the synthesis of Zn-MOF-74, 0.25 g of dihydroxy terephthalic acid (DHTA) and 1 g of zinc nitrate tetrahydrate [Zn $(NO_3)_2 \cdot 4H_2O$] were mixed to create a solid mixture. The mixture was dissolved in 50 mL of dimethylformamide (DMF) with constant stirring at 360 rpm. After 5 minutes of stirring, 2,5 mL of H_2O was slowly added to the mixture dropwise for 15 minutes while continuing to stir. The mixture was kept without stirring at room temperature for 30 minutes then transferred into a Teflon-lined autoclave and placed in the oven at 100°C for 24 hours to allow for the crystallization process to occur forming yellow needle-like crystals of Zn-MOF-74. After cooling the autoclave to room temperature, the mother liquor was decanted.

The unused DMF solvent was then replaced with methanol. For 3 days, the solid crystalline particles were submerged in methanol, which was replaced every 24 hours (Luu et al., 2020). Vacuum filtration was used to remove the liquid from the solid particles and allowed to dry overnight. At reaction temperatures of 100, 110, and 125°C, the process was repeated for reaction periods of 8, 12, 24, and 48 hours. To verify the repeatability of the procedure and the accuracy of the data collected, each experiment was conducted three times.

Activation

To activate the sample, it was placed in the oven at 150°C for 12 hours. This allowed the methanol and some residual moisture adsorbed on the material to be removed through evaporation. This allows for the open-metal sites of the porous crystalline MOF material to be exposed to enable the adsorption of CO_2 molecules (Choi et al., 2017).

Characterization

To characterize and analyse the physicochemical properties of the synthesized samples different analytical techniques were applied. The BET analysis was conducted using instrument Tristar II. from Micromeritics. The samples were degassed at 90°C for 1 hour, then at 200°C for 2 hours. BET surface area, pore size and volume were measured using nitrogen at 77 K (-196°C). PerkinElmer UATR Two FTIR spectrometer was used to obtain the spectra of the samples in this study. The samples were characterized at room temperature. All spectra were obtained with an 8 cm^{-1} resolution and a total of 12 scans per spectrum in the frequency range of 4000 - 500 cm^{-1}.

High-quality, low-voltage images were produced using instrument VEGA 3 TESCAN SEM by slightly electrically charging samples at 10 kV. SEM has the benefit of not requiring insulating materials to be coated with conducting materials. The XRD analysis was conducted using the PANalytical X'pert PRO instrument. It was conducted with a goniometric assembly containing an X-ray tube and a detector which rotate at 2-Theta (2θ) angle relative to each other over a range from 5^o to 90^o. X-ray diffraction was fitted with a Cu Kα (λ = 0.154 nm) radiation source with a tube operating at 45 kV and 40 mA and with a beam size of 10 mm. The sample was glued on a metal slide. Data was collected at 0.017° 2θ per 30 seconds. TGA curves were acquired using TA Instruments TGA Q500, in the temperature range of 30−800°C under a nitrogen atmosphere at a heating rate of 10°C/min.

RESULTS & DISCUSSION

Physical properties

Crystallinity (X-Ray Diffraction)

The effect of varying synthesis time and temperature on the crystallinity of the material was studies through XRD characterization as shown in Figure 12 (a) and (b). When the synthesis duration was kept constant at 24 hours, similar patterns were obtained for all synthesis temperatures, with large sharp peaks at 2θ of 11, 17 to 20, 38°, indicating that the material was highly crystalline. This confirmed that the crystalline material can be successfully synthesized at these temperatures, including the 110 or 100°C reported by Doan et al. (2019). The intensity of the peaks slightly increased with increasing synthesis temperature. This agrees with Haider et al. (2024), mentioning that increased temperatures promote the growth of crystals by augmenting the mobility of solute particles, which enables molecules or ions to readily migrate and adhere to the crystal lattice and thus increasing the particle size. The peak with the highest intensity was at 125°C, when 2θ was 19.5 ° suggesting that this temperature produced the most stable crystalline structure.

In Figure 12 (b), similar XRD patterns for 8 and 12 hours with main peaks at when 2θ was 11, 18 to 19, 25, and 28° were observed. The intensity of the peaks reduced with an increase in synthesis time confirming that increasing the synthesis time has a noticeable effect on the crystal structure of the samples. The trends exhibit a progressive loss of crystallinity and final crystal amorphization at 48 hours with irregular particle arrangement, agreeing with Nguyen et al. (2020) who reported that when the reaction time was increased at constant temperature, conversion of the crystalline phase into amorphous takes place due to interdiffusion at an atomic level between crystalline layers. Furthermore, imperfect lattice structure was produced suggesting that when the synthesis period is prolonged, the remaining reactants and solvent may weaken the structure of MOFs and compromise their crystallinity.

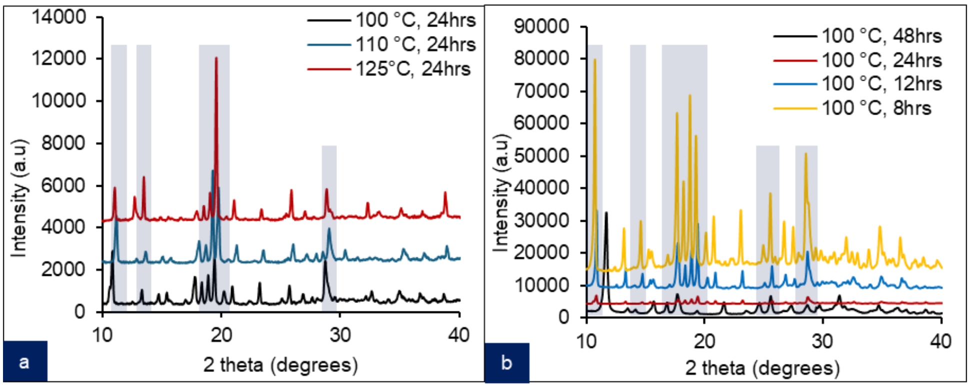

Figure 12: *XRD results for varied synthesis (a) temperature and (b) time.*

Scanning Electron Microscopy (SEM)

The SEM micrographs of the Zn-MOF-74 synthesized at 100, 110, and 125°C for 8 hours are presented in Figure 13. At 100°C, crystalline particles were observed to have a smooth surface and particle size range of 2 to 10 micrometers (µm) which was uniform. For 110°C, the particles were larger, rougher, crystalline isolated needle-like shaped with the length of approximately 40 µm whereas the 125°C particle were similar however, larger particle sizes with an irregular arrangement. The particle size, crystallinity and surface roughness increased with increased synthesis temperature agreeing with the XRD patterns in **Figure 12**. Furthermore, surface roughness is crucial for CO_2 adsorption, Cui et al. (2024) found that the adsorption of CO_2 increased as surface roughness increased.

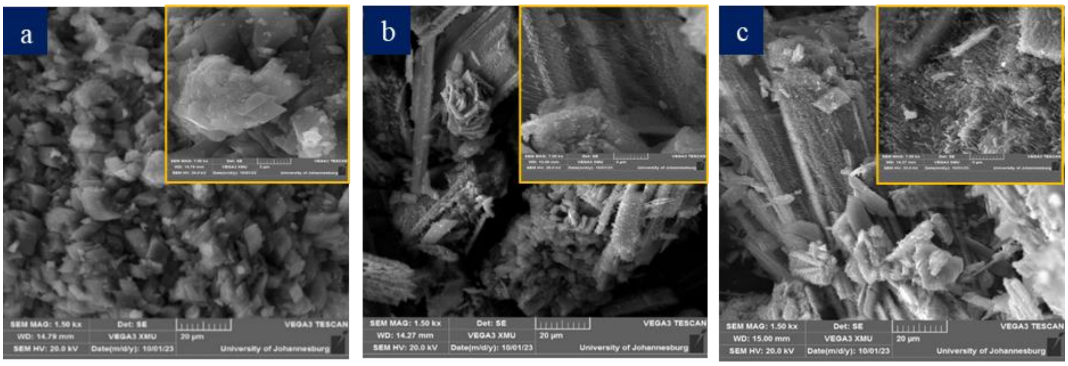

***Figure 13**: SEM images with 7000× and 1500× magnification for Zn-MOF-74 samples synthesized at (a)100°C, (b) 110°C, and (c) 125°C for 8 hours.*

When the synthesis time increased from 8 to 24 hours, the particles changed from smooth, crystalline to rough needle-like crystalline particles with more disorganized particle arrangement and size distribution as illustrated in Figure 14. Agreeing with Han et al. (2023)'s study that mentioned that metal-oxygen clusters and organic linkers self-assemble during the crystallization process that creates MOFs. Since synthesis time influences MOF crystal nucleation and development, precise control over morphology and size is possible and thus, the rate of crystallization increased with the duration of synthesis.

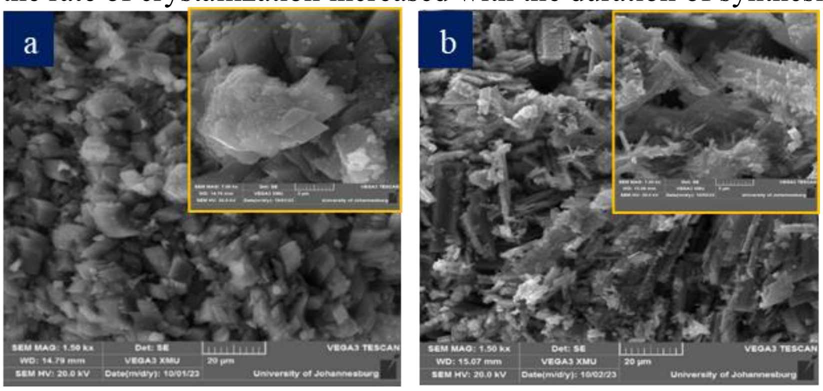

***Figure 14**: SEM images with 7000× and 1500× magnification for Zn-MOF-74 samples synthesized at 100 °C for (a) 8 hours, and (b) 24 hours.*

Textural properties (Brunauer-Emmett-Teller)

Figure 15 (a) and (b) show the BET isotherm results generated through the low-pressure N_2 gas adsorption for the material synthesized at temperatures of 100°C and 125°C for 24 hours, respectively, showing the amount of nitrogen adsorbed and desorbed on the MOF sample with increased relative pressures. The BET curves show a Type III isotherm was obtained showing the formation of a multilayer. The adsorption isotherm shows a progressive rise in adsorption of N_2 at relative pressure (P/P_0) from 0.6 to 0.995, indicating the presence of micropores (del Rio et al., 2022) and that the material was capable of successful gas adsorption. Conversely, the desorption isotherm indicates a decrease in gas quantity when the relative pressure decreases. The 100°C sample adsorbed significantly higher volume of N_2, of 76 cm^3/g compared to the 125°C which adsorbed 31 cm^3/g. This was due to their surface areas of 20 m^2/g and 10.5 m^2/g respectively as shown in Figure 16.

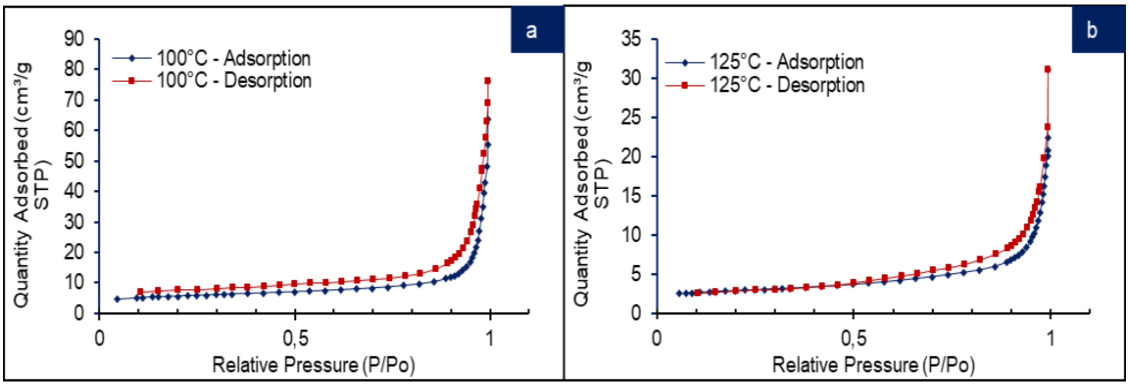

***Figure 15**: BET results for synthesis at (a) 100°C, and (b) 125°C for 24 hours*

The highest recorded surface area was 55 m^2/g, 37 m^2/g, and 32 m^2/g at synthesis conditions of 100°C, 12 hours; 125°C, 48 hours and 100°C, 48 hours with relatively high pore diameters of 20, 60 Å, and 72 Å, respectively, as shown in Figure 16. Chiang et al. (2020) stated that porous structure and surface functional groups of adsorbents have a significant impact on the CO_2 adsorption performance. Varied sizes of micropores were achieved, ranging from super-micropores (between 7 and 20 Å) to mesopores (more than 20 Å) (Ambroz et al., 2018). The primary cause of the significantly higher CO_2 uptake is the pore size and adsorption pressure. According to W. Liu et al. (2021), the adsorption capacity of the material will be low if the pore diameter is exceptionally large, and the specific surface area is small. The shielding effect for molecules with larger diameters is enhanced when the pore diameter is too small because it limits the physical adsorption of gas molecules on the solid surface. Only pores with diameter of less than 3.5 Å which is the diameter if CO_2 can limit sorption. Therefore, high adsorption capacity is expected for 100°C, 12 hours and 125°C, 48 hours. There is no direct correlation between the synthesis time or temperature on the pore diameter and the surface area of the Zn-MOF-74 samples.

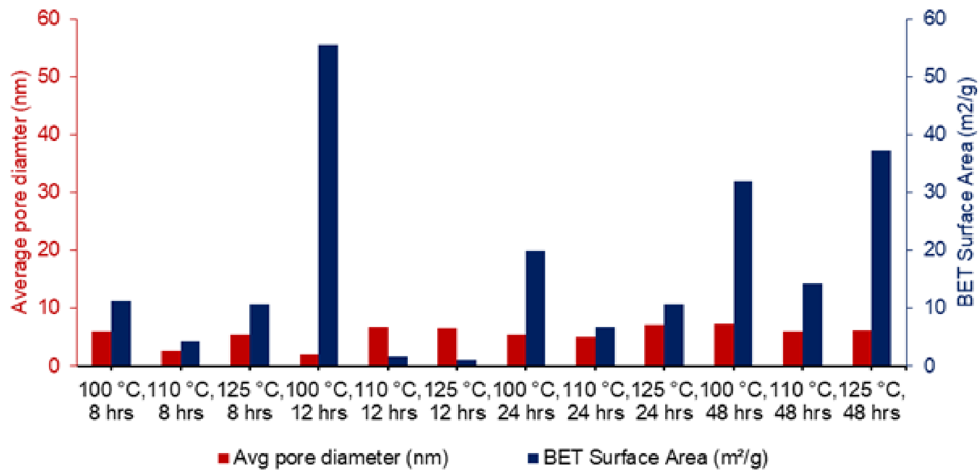

***Figure 16:** Surface area and average adsorption pore diameter at different synthesis temperatures and times.*

Chemical Properties

Thermal stability (Thermogravimetric analysis)

The TGA measured the mass loss that occurred in a sample when it was heated steadily in a N_2 atmosphere. Figure 17 shows the effect of varying synthesis temperature on the thermal stability of the Zn-MOF-74. The initial weight percentage decrease was attributed to the removal of the residual moisture and solvent at temperatures of below 150°C. A plateau phase where the solvent-free evacuated MOF is stable followed up to 430°C, and as the framework started to deteriorate at the second stage of decomposition and a subsequent mass loss process followed (Healy et al., 2020). This meant that it could be suitable for CO_2 capture from flue gas from coal-fired power plants without the need for cooling the flue-gas stack. The trend stabilized again at approximately 500°C after the second decomposition where there was residue of the material. In comparison to 110°C and 100°C 125°C showed to retain more mass, making it the most suitable for synthesis temperature suitable for CO_2 capture application.

The effect of synthesis time on the thermal stability of the material is shown in (b). Decreasing the synthesis time increased in mass retention. Synthesis time of 48 hours was the most stable compared to 24 and 8 hours however, it retained less mass. The 8 hours period was outstanding in retaining mass but showed a very unstable trend which may be not effective for adsorption at higher temperatures. After the removal of the solvent, open metal sites are present which have a high affinity to CO_2 molecules as stated by Norouzbahari et al. (2023), and all synthesis conditions showed thermal stability up to 430°C.

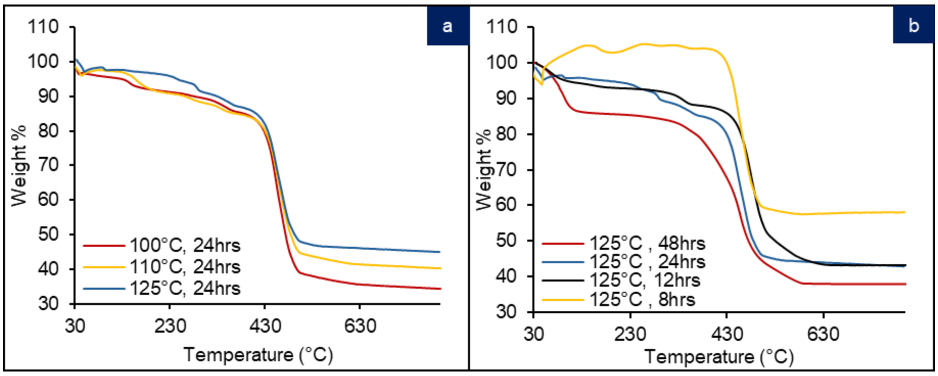

Figure 17: *TGA results for varied synthesis (a) temperatures and (b) time.*

Surface chemistry (Fourier Transform Infrared Spectroscopy)

The FTIR was used to determine the success of the MOF synthesis and suitability in its applications in post-combustion carbon capture by indicating functional groups present in the materials. Figure 18 show all the spectra recorded for different synthesis time and temperatures. In Figure 18, the spectra show a similar trend except for the 48 hours synthesis time. The C=O at 1640 cm^{-1} that is attributed to the presence of carboxylic acid disappeared in the 110°C. The conjugate alkene (C=C) at 1620 cm^{-1} was not present for 125 and 110°C at 48 hours and for the 24 hours samples, this showed the instability within the 48 hours MOF structure. The OH bend at 1411 cm^{-1} was assigned to carboxylic acid from the DHBTA which was intermolecular connected within the Zn-MOF-74. At 1222 cm^{-1}, amine (C-N) was present for 125 and 100°C at 48 hours, which is advantageous due to its high tolerance against moisture. The C-O (tertiary alcohol), 1200 cm^{-1} is present for 48 hours only, C=C (alkene), 864 cm^{-1} is present for 48 hours only. Espinosa-Flores et al. (2023) mentioned that the adsorption of CO_2 could be efficiently increased by the doped oxygen-containing functional groups, such as carboxyl and hydroxyl groups. The presence of these functional groups in the samples indicates that the synthesis of Zn-MOF-74 was successful and agrees with Liu et al. (2018).

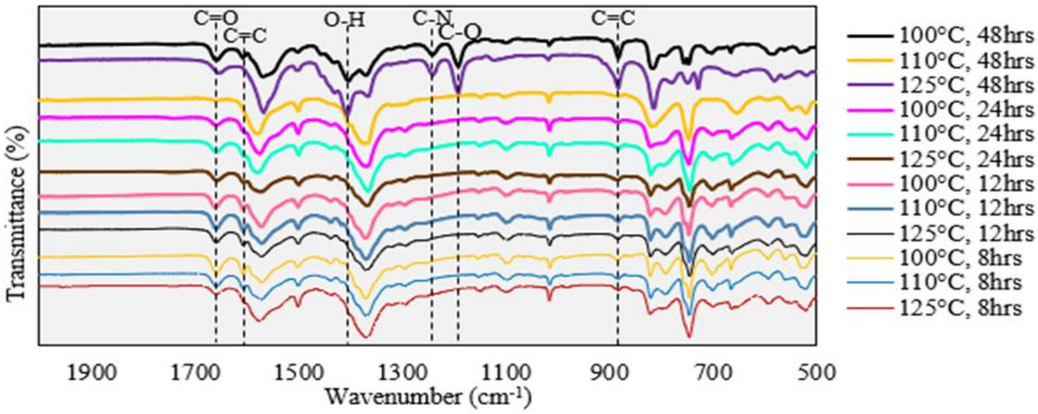

Figure 18: *FTIR results for samples synthesized at varied temperatures and time.*

CONCLUSIONS AND RECOMMENDATIONS

It may be concluded that Zn-MOF-74 was successfully synthesized as the carboxyl and hydroxyl functional groups which are crucial for CO_2 adsorption were present as depicted by the FTIR. Changing the synthesis temperature and time influenced the resulting physical and chemical characteristics of the material and consequently its potential applicability in CO_2 capture. The samples were thermally stable for up to 430°C and thus applicable for CO_2 capture from the exit flue without the need of pre-cooling. Prolonged synthesis times should be avoided as the unused reactants and solvent may weaken the MOF structure and the thermal stability and crystallinity of the MOF is compromised. Furthermore, the prolonged periods produce MOF increase the pore diameter of causing the samples to be less suitable for CO_2 adsorption capacities. The material synthesized at 100°C and for 12 hours and 125°C and for 24 hours has a mesoporous structure with a large surface area, making it appropriate for gas storage and separation applications.

It is recommended to evaluate effects of the synthesis conditions on the performance of Zn-MOF-74 during the CO_2 capture using a synthetic flue gas from a typical coal-fired power plant containing 78% N_2, 16% CO_2, and 6% O_2. The materials should be evaluated in real flue gas conditions to determine the effect the presence of impurities in the flue gas on the performance of the materials. The stability, durability, regeneration, and reliability of the MOF samples during CO_2 adsorption-desorption cycles should also be evaluated.

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PASTEURIZATION FOR BETTER BIOGAS GENERATION AND ECOLOGICALLY FRIENDLY FERTILIZER USING COST-EFFECTIVE TECHNOLOGY

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ABSTRACT

This article presents the findings from an experiment on the impact of pasteurizing cow manure on biogas production and concentration. The study involved two trials conducted in separate bio-digesters (D1 and D2) with a capacity of 18.0 liters each. Each digester contained a mixture of 16.0 liters, consisting of 4.0 kg of cow dung, cow rumen, and blood. The material in digester mixture (2) underwent pasteurization in a water bath at a controlled temperature of 70°C. Digester 1 yielded an average of 425 liters of biogas with a methane concentration of 62% over a period of 49 days, while digester 2 produced 328 liters with a methane concentration of 79.77% in 26 days. The results of this study indicate that pasteurizing cow dung enhances methane concentration (15-17%) and increases the daily methane production rate by 21.2%. The study suggests that pasteurization could be explored as a method to enhance biogas output while reducing the overall cost of methane production. The research recommends the use of cost-effective digesters with pretreatment as a viable approach to boost energy production and promote the use of environmentally friendly fertilizers.

Keywords: cow manure, biogas, pasteurization, methane concentration, appropriate technology.

INTRODUCTION

Biogas serves as an eco-friendly energy source that can be utilized directly for heating, generating electricity, or providing mechanical energy for transportation. Alternatively, it can be converted into liquid fuels, utilized in fuel cells, or upgraded to bio-methane. In addition to household applications, some internal combustion engines now operate on biogas instead of gasoline, as noted by Qian et al. 2017. The objective of this study is to facilitate the establishment of commercial biogas plants and address barriers hindering their widespread adoption by optimizing plant size and enhancing production quantity and quality. This topic has been extensively explored in the literature by Kemausuor, Adaramola, and Morken 2018), Darwesh and Ghoname 2021 as well as Bulatov et al. 2020. Furthermore, biogas production not only contributes to the energy sector in African communities but also meets the requirements of appropriate technology while producing environmentally friendly effluents. Certain feedstocks are unsuitable for biogas production due to factors such as resistance to microbial digestion, slow digestion rates, or the presence of inhibitors. The "pretreatment" process eliminates these obstacles and makes the organic content of the substrate accessible to the microbial community. Various pretreatment methods exist, including physical, chemical, physicochemical, and biological approaches, as discussed by Patinvoh et al. 2017. Among these methods, heat treatment and agitation represent the simplest forms of physical pretreatment.

The research investigates the direct generation of biogas through the decomposition of biomaterials, including cow dung, rumen content, blood, and similar substances. The pasteurization of cow dung plays a crucial role as a pretreatment step to enhance both production efficiency and sanitation. Similarly, other materials, such as organic fertilizer derived from animal by-products, require pre-heat treatment to optimize the process (Avolio et al. 2023).

Shape of biogas digesters: Biogas digesters can have many forms depending on their size. Small experimental digesters range in size from a few liters to a full digester, depending on academic needs. Home sizes can reach a few cubic meters, constructed of fixed roof or floating roof or dome. Finally, there are big industrial digesters that are hundreds of cubic meters in capacity. The advent of new material affected the technology of biogasigesters such that different sizes of digesters and gas holders are made of special flexible material you can find medium. Figure 1 illustrates the general shape of bio-digester. This type digester characterized by low cost flexibility, and can be used for continuous or batch fermentation.

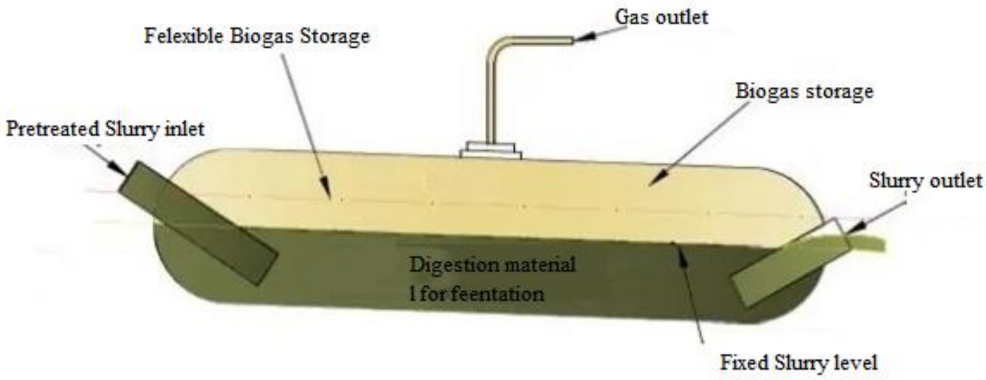

Figure 1: Modern flexible balloon digester and gas holder

ASSOCIATED LITERATURE

The potential for biogas production from various resources and its subsequent utilization in power generation has been quantified, with an estimated 11.65Mm3/d of biogas production potential capable of generating 3059.7GWh/y of electricity in a single state (Yaqoob et al. 2021). Research on biogas has focused on both production rate and quality, with Week 2 yielding the highest volume of biogas and Week 4 yielding the lowest volume. (Rabah A.B. et al. 2010). Pasteurization is a heat-treated procedure at 70°C for 60 minutes, while integrated thermophilic sanitation (ITS) requires 52°C for 10 hours. Laboratory experiments have shown that pasteurization can be carried out within the biogas digester. Research conducted by (Nordell et al. 2022), (Grim et al. 2015), indicated that there was no significant difference in methane production and concentration between pasteurization and ITS. The utilization of bio-digester sludge or slurry for agricultural purposes has been on the rise, including fertilizing agricultural lands, forests, and the restoration of damaged areas. However, recent studies have highlighted the presence of numerous pathogenic microorganisms in bio-waste intended for land application over the past two decades. According to (Liu, Lendormi, and Lanoisellé 2019), less than a quarter of the biogas energy is utilized for the heat treatment required for hygienization, which can impact the generation of bio-methane potential.

Shape of biogas digesters: Biogas digesters come in various shapes depending on their size. Small experimental digesters can range from a few liters to a full digester, catering to academic needs. Household digesters can reach a few cubic meters in size, while large industrial digesters can have a capacity of hundreds of cubic meters. Sterilizing pretreatment can be applied to digesters of all sizes.

Composition of Biogas: Biogas is typically composed of 55% to 70% methane (CH_4), 30% to 45% carbon dioxide (CO_2), less than 100 ppmV of hydrocarbons (<100 ppmV), 1000–3000 ppmV of hydrogen sulfide (H_2S), and 80–100 ppmV of ammonia (NH_3). Additionally, there are traces of siloxanes present in biogas. Various species of microbes break down organic material in multiple phases during anaerobic digestion, resulting in the production of biogas, which is mainly methane and carbon dioxide, and digestate, a slurry or solid fraction remaining from the treated substrate. Most organic source materials can be utilized for biogas production, except for lignin, which cannot be decomposed anaerobically. The composition of the substrate influences the output of biogas and its methane content. Table 1 illustrates the constituent composition of biogas in comparison to landfill gas and natural gas (Patinvoh et al. 2017).

Table 1: *The composition of biogas, landfill gas, and natural gas.*

	Biogas *	**Biogas	**Landfill gas	**Natural gas
Methane (vol-%)	55-70	60 –70	35 – 65	81-89
Other hydrocarbons (vol-%)	<100ppm	0	0	3.5-9.4
Hydrogen (vol-%)	-	0	0	0-3
Carbon dioxide (vol-%)	30-45	30-30	15-50	0.67-1
Nitrogen (vol-%)	-	~0.2	0 - 40	0.28-14
Oxygen (vol-%)	-	0	0 - 5	0
Hydrogen sulphide (ppm)	1000-3000	0-4000	0-100	2.9
Ammonia (ppm)	80-100	~100	~5	0
Lower heating value (kWh/Nm3	-	6.5	4.4	8.8-11

* (Leonzio 2016) ** (Patinvoh et al. 2017)

MATERIALS AND METHODS

The study was conducted in a laboratory setting to explore the effects of cow dung pasteurization on the rate of biogas production and the percentage of methane. Two small-scale anaerobic digestion processes were carried out in bio-digesters (D1 and D2) created from sealed 18.0L plastic containers. The aim was to compare the qualities of the two bio-digesters under anaerobic digestion conditions. Both bio-digesters were filled with a mixture of cow dung, rumen material (dry matter), and unmeasured pH water, with a capacity of 16.0 L and the remaining space utilized for gas collection. The content of the two bio-digesters is presented in Table 2.

Pretreatment Pasteurization of bio-digester (D2)

The blend is housed in a 17.0 liter metal receptacle, which is positioned inside a larger aluminum vessel holding 25 liters of water. Following this, the blend was placed on a stove and gradually heated to 70°C using hot water, as illustrated in Figures 2 and 3. In accordance with the pasteurization process described in (Nordell et al. 2022) the blend was stirred at this temperature for an hour using a plastic rod after reaching 70°C. It was then filled with a unique paste and placed into the biodigester (D2).

Experimental setup

The water displacement method was utilized to measure the flow rate of biogas and biogas after CO2 absorption. Biogas is a mixture that can include water vapor, hydrogen sulfide, nitrogen, oxygen, ammonia, siloxanes, and particles, alongside methane and carbon dioxide. Nevertheless, carbon dioxide predominates in the gas composition, accounting for 30-45% of the total. The absorption of CO2 by sodium hydroxide solids follows the chemical equation: 2NaOH (s) + CO2 (g) → Na2CI3 (aq) + H2O (l). The connection of various components was achieved using 0.3-inch hoses, as depicted in Figure 4. The experiment was conducted at room temperature; however, it is crucial to operate similar digesters simultaneously as the temperature environment significantly impacts performance.

Table 2: Compositions of raw material mixture in bio-digesters (1) and (2)

Raw material	Bio-digester (D1) 18.0 L	Bio-digester(D2) 18.0 L
Cow dung (dry matter)	4.0 kg	4.0 kg
Water	12.0 L	12.0 L
Total amount	16.0 L	16.0 L
Dry matter percentage	25%	25%
Pasteurization cow dung	No	Yes

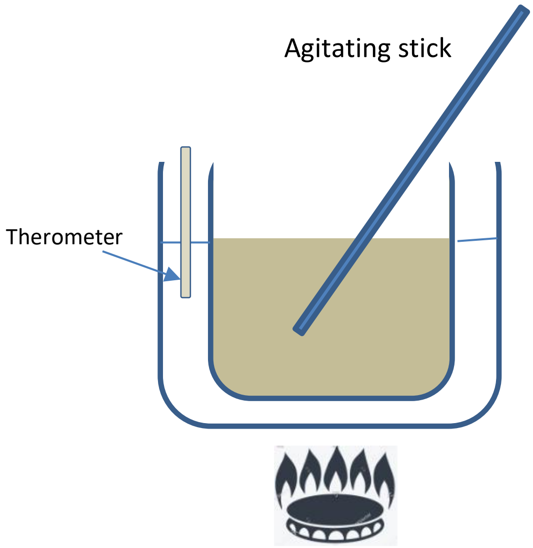

***Figure 2**: Simple Laboratory water bath for pasteurization*

***Figure 3**: Laboratory water bath pasteurization*

Figure 4: *Bio-digesters (D1) and (D2) installed in experiment system*

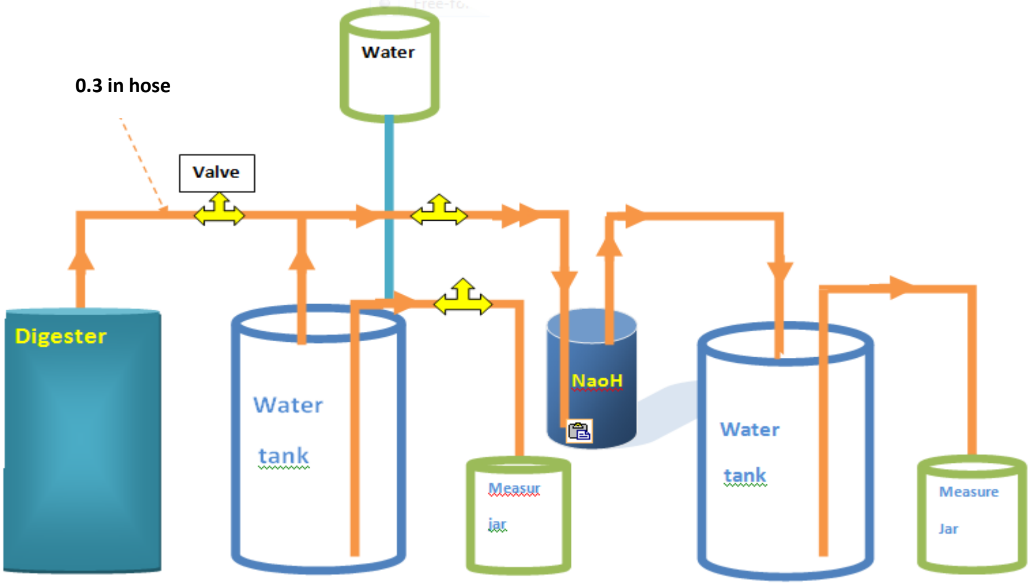

Figure 5: *Schematic diagram of digester connections*

RESULTS AND DISCUSSION

The recorded biogas production in liters, determined through water displacement, is presented in Table 2. The composition technique was utilized to analyze the biogas. Alternatively, membrane separation could be employed for separation, as demonstrated by(Francesco Zito, Brunetti, and Barbieri 2022). Biodigester (D2) commenced operations after 12 hours, while biodigester (D1) started after 18 hours. Methane production in biodigester (D1) began at a rate of sixteen percent after five days, whereas it initiated on the first day in biodigester (D2). The acceleration of chemical reactions, such as the conversion of protein to amino acid chains, carbohydrates to sugars, and fats to long-chain fatty acids, can be achieved by heating to a specific temperature for a set duration. This suggests that pasteurization expedites the anaerobic process, as evidenced by the earlier onset of biogas production in biodigester (D2). These processes are commonly referred to as hydrolysis. The uniformity and dark color of the pasteurized mixture indicate the color changes that occur during the breakdown and decomposition of fats and proteins. Moreover, the early increase in methane content in the biogas of biodigester (D2) implies that thermophilic conditions and pasteurization support the growth of acetogenic bacteria by maintaining a consistent temperature (acetogenic bacteria are particularly sensitive to temperature fluctuations).

Table 2: *Daily result production of bio-digester (D1) and (D2)*

	Bio-digester D1			Bio-digester D2		
Day	Biogas production L	Methane production L	Methane percentage %	Biogas production L	Methane production L	Methane Percentage %
1	0.1	0	0	2.6	1.5	58.8
2	0.5	0	0	3.6	2.225	62.2
3	1.2	0	0	4.5	3.4	75.6
4	1.4	0	0	7.4	5.625	76
5	2.1	0	0	7.3	6.725	92.4
6	3	0.5	16.7	7.3	5.35	73.3
7	5	1.3	25	8.8	6.65	75.3
8	4.9	2.4	50.1	10.9	9.9	90.9
9	7.7	4.5	59	14.7	12.15	82.8
10	9.8	8.4	85.7	23.2	19.625	84.7
11	18.6	15.6	83.8	26.6	23.75	89.4
12	34.8	17.6	50.6	38.4	29.325	76.5
13	46.9	24.2	51.5	42	29.975	71.5
14	41.1	31.1	75.7	28.3	24.775	87.6
15	29.1	22.8	78.5	27.6	23.6	85.7
16	26.9	20.1	74.9	25.9	20.75	80.2
17	25.9	20.8	80.4	11.2	9.7	87
18	19.2	14.6	75.8	12.6	9.425	75.1
19	11.2	6.9	61.4	14	10	71.4
20	20.5	7.1	34.3	13.8	10.3	74.6
21	22.4	11.2	50	6.7	6.025	81.8
22	14.5	8.1	55.7	5.4	4.3	79.6
23	13.1	11.4	87.2	9.8	6.8	69.4
24	10.1	6.1	59.9	10.5	7.575	72.1
25	6.5	3.7	57.1	10	8.35	83.5
26	2.9	2.2	75.9	9.8	7.9	80.6
27	2.9	2.8	95.7			
28	2.3	2.1	93.3			
29	2.1	1.6	75			
30	1.5	1.2	81.4			
31	2.8	1.7	60.7			
32	3.2	2.1	64.6			
33	4.2	3.5	83.3			
34	4	3.1	77.2			
35	2.8	0.9	30.4			
36	3.6	0.1	2.8			
37	3.5	1.2	35.4			
38	3.8	3	77.6			
39	2.8	1.8	64.3			
40	2.7	0.8	29.4			
41	2.2	0.9	40.9			
42	2	0.9	45.5			
43	1.7	0.1	7.1			
44	1.1	0.1	9			
45	0.9	0.2	24.4			
46	0.8	0.1	13			
47	0.8	0.1	13			
	430.1	268.5	62.5	379.5 (12% less)	302.7 (13%more)	79.77 (27% more)

Prouction period is redused from 47 to 26 days.

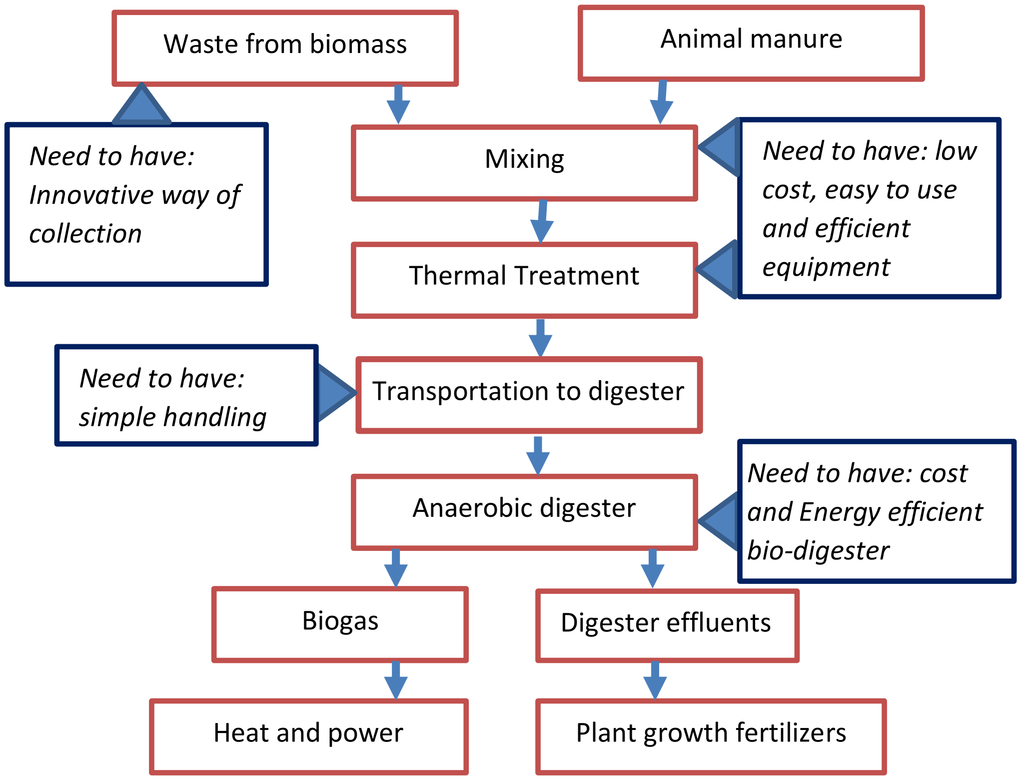

Figure 5: *Detailed Steps flowchart applicable to biogas production process*

CONCLUSION

Biogas production is a key factor in the sustainable expansion of energy supply and the reduction of greenhouse gas emissions. The research conducted revealed that the process of pasteurizing cow manure significantly boosts daily methane generation and enhances the methane concentration in biogas output by an average of 27%. By implementing pasteurization, the time required for biogas production is cut in half, allowing for an additional production period. This advancement in biogas generation not only benefits agricultural communities by providing energy and eco-friendly fertilizers but also aids in the removal of water vapor, ammonia, and hydrogen sulfide from biogas, as demonstrated in the experimental setup. Further exploration is necessary to develop straightforward and effective methods for pasteurization pretreatment.

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INVESTIGATION OF TILAPIA FISH SCALES AS A GREEN CORROSION INHIBITOR FOR MILD STEEL IN REINFORCED MATERIAL

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ABSTRACT

Due to the effect of climate change, acid rain has been identified as a major contributing factor to the corrosion of mild steel used in reinforced structures. The research undertaken was to study Tilapia fish scales as a green corrosion inhibitor because of its abundance in both organic components such as collagen ($C_{12}H_{19}N_3O_5$) and inorganic components such as hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$). The prepared fish scales were investigated as a corrosion inhibitor for mild steel while exposed to simulated acid rain environment. The mild steel coupons were immersed in simulated acid rain solution with 1M H_2SO_4 in different acidic pH content ranging from pH 3, pH 3.5, pH 4 and pH 5, and inhibitor amounts of 2g, 3g and 4g. The results obtained from the long-term immersion coupon tests was found to have a maximum inhibition efficiency (%IE) of 92.74% while for the short term coupon tests (electrochemical potentiostatic) an inhibition efficiency of 92.4% was recorded at pH 5 with 4g inhibitor condition. The metal surface was studied by Scanning Electron Microscope (SEM) analysis to evaluate the reduction in corrosion effects due to the fish scale inhibitor adsorption. Adsorption studies were done using theoretical models, such as Langmuir, Freundlich and Frumkin isotherms. The Langmuir isotherm showed the best fit of results from the calculated R^2-values obtained as they were closure to a value 1. The results obtained clearly demonstrate that fish scales have proven to be a non-toxic, eco-friendly inhibitor of mild steel in the prevention of aggressive corrosion in simulated acid rain.

Keywords: Green corrosion inhibitor; Tilapia fish scales; mild steel; simulated acid rain, climate change.

1. INTRODUCTION

When exposed to certain acidic environments, mild steel degrades through a process called corrosion, which is an undesired natural process which takes place by ectrochemical and chemical interactions. Corrosion of steel found in infrastructure, such as bridges, buildings, towers, pipelines, etc., is likely to develop quickly over the next few years due to the predicted climate change circumstances which results in the formation of acid rain. The financial impact as a results of metal alloys corrosion is estimated to be 2.5 trillion dollars (USD $) worldwide. In South Africa alone the direct cost is about R130 billion per year and cost the country about 4% of the gross domestic product. The corrosion phenomena mainly of reinforcement material have been an ongoing, expensive issue (Brimblecombe & Grossi, 2007), whereby carbon dioxide (CO_2) in the atmosphere reacts with water to form carbonic acid (H_2CO_3), which is the main source of acid rain. Regular, unpolluted rain has a pH of approximately 5.6, while acid rain has been found to have a pH of 4-5. In addition, due to the pH scale's logarithmic structure acid rain with a pH of 4.6 is 10 times more acidic than normal rain (Schwab *et al.,* 2016).

It is important to develop eco-friendly and cost effective inhibitors, as some chemicals inhibitors currently in use are toxic and of high cost. Natural, eco-friendly resources such as fish scales bio waste was used in this research investigative study. Costly chemicals used as corrosion inhibitors for metal can now be substituted by natural substances of plant, animal and fruit origin that are inexpensive and easy to find (Gunavathy & Murugavel, 2013). These compounds contain different organic compounds e.g. alkaloids, lignin, tannins, amino acids, pigments. The majority of chemicals that have an inhibitory effect on corrosion are found in the aqueous extracts of some plant parts, such as fruits, fruit shells, stems, leaves, and seeds (Goni & Mazumder, 2019).

Tilapia fish scales contain 40% to 50% organic material (collagen, lipids, proteins, and vitamins), as well as inorganic substances like calcium and phosphates, these compounds are considered the effective ingredients. Ten (10) grams of fish scales, which can be found on one or two fish, can yield about 200 milligrams (mg) of collagen. Since fish scales are typically discarded in landfills which may also lead to land pollution, obtaining them is fairly inexpensive and easy (Chinh *et al.,* 2019). Methods such as electrochemical impedance spectroscopy, weight loss technique, adsorption studies, surface studies are commonly used in the corrosion inhibition studies as a way to determine the effectiveness of the inhibitor while protecting the surface of metal against corrosion (Ebenso, *et al*. 2008, Umoren *et al.* 2015).

2. RELATED STUDIES

Green corrosion inhibitors are crucial because they protect the environment as they are non-toxic and contains crucial elements such as P, S and N atoms. Plant leaf extract has been the subject of much investigation as a corrosion inhibitor for mild steel (Abiola *et al.,* 2007; Abiola & James, 2010; Action, 2020; Adejo *et al.,* 2013; Al-Moubaraki & Al-Malwi, 2022; Chauhan & Gunasekaran, 2007; Dakmouche *et al.,* 2009; Davis, 2000; Dehghani *et al.,* 2019; Department, 2014; Devikala *et al.,* 2019; Ebenso *et al.,* 2008; Haldhar *et al.,* 2018; Lu & Luo, 2020; McEwan, 2004; Mo *et al.,* 2016; Noor, 2008, 2009; Oguzie, 2010; Okafor et al., 2008; Orubite-Okorosaye & Oforka, 2004; Orubite & Oforka, 2004; Parikh & Joshi, 2004; Quraishi *et al.,* 2010; Schwab *et al.,* 2016). The inhibition effect of some fruits have also been investigated using different techniques and has demonstrated a positive outcome with good inhibition efficiencies (El-Sayed *et al.,* 2001; Fekkar *et al.,* 2020; Ibrahim & Habbab, 2011; Ji *et al.,* 2015; Loto *et al.,* 2003; M'hiri *et al.,* 2016; Manikandan *et al.,* 2019; Mobin *et al.,* 2019; Okafor & Ebenso, 2007; Rocha *et al.*, 2014; Rosli *et al.,* 2019; Sanaei *et al.,* 2019; Schwab *et al.,* 2016; Sedik et al., 2020; Singh *et al.,* 2010; Umoren *et al.,* 2015; Valek & Martinez, 2007). Few studies have been carried out to demonstrate the use of animal and fish extract as corrosion inhibitors (Amanah *et al.,* 2023; Basik & Mobin, 2020; Gapsari *et al.,* 2022; Olawale *et al.,* 2019; Subhashini *et al.,* 2008).

3. METHODOLOGY

3.1. Preparation of mild steel coupons

Table 2: *The composition of mild steel*

Element	C	St	Mn	S	P	Cr	Ni	Mo	Cu	V	Al	N	B	Fe
%weight	0.19	0.23	1.12	0.004	0.09	0.036	0.021	0.003	0.019	0.021	0.001	0.006	0.001	0.978

The mild steel coupons for both the long-term and short-term coupon tests had compositions illustrated in Table 1. For the long-term (weight loss) tests the coupons were cut by the use of a cutting machine Brilliant 200 to dimensions of 30×32×8 mm. The coupons for the short-term electrochemical tests were cut to 10 x 10 mm. The coupons were grinded and polished using the polishing machine Struers – TegraPol 11. This was done by using silicon carbide papers and grinding the metal surface gradually from P180, P320, P500, P600, P800, P100 to P1200 grit. They were then washed with acetone, and then dehydrated with absolute ethanol. All coupons for long-term tests were placed in a desiccator 24 hrs before the tests while the coupons for short-term test were cold mounted using the fibre glass liquid.

3.2. Preparation of fish scale inhibitor

Tilapia fish scales were collected from a local fish market, washed with distilled water and thereafter dried at a temperature of 70-80̊ C for 7-8 hours using a laboratory oven LASEC-EMF 260. An electric grinder was used to grind down the dried fish scales to powder form and then sieved in order to separate the grinded fish scale sample into uniform particle size of 300 µm. The grinded fish scale sample was then taken through the maceration process, whereby bout 500 ml of 98% of ethanol was measures into a conical flask to have a ratio of 1:5 sample to ethanol. The flask was closed with a cap and cellophane wrap was used to make it airtight and thereafter left for 4 days (96 hrs) to allow for good residence extraction time. After 4 days the mixture was run through a 200 µm sieve and the filtrate was then poured into a rotary evaporator running at 80 ℃ in order to remove the ethanol from the macerated fish scale sample.

3.3. Preparation of simulated acid rain

The simulated rain water was prepared by using deionized water and analytical salts as indicated on the below Table 2 (Pilić *et al.,* 2018). One (1) M/L sulphuric acid was used to adjust the pH to four (4) different concentrations of 3, 3.5, 4 and 5.

Table 3: *Inorganic salts used for the preparation of simulated acid rain solution*

Component Chemical type	**Concentration (g/L)**
Ammonia nitrate (NH_4NO_3)	0.13
Magnesium sulphate ($MgSO_4$)	0.31
Sodium sulphate ($NaSO_4$)	0.25
Potassium carbonate (KCO_3)	0.13
Calcium chloride ($CaCl_3$)	0.31

3.4. Long term coupon tests (weight loss method)

The technique used was to first weigh the prepared, polished mild steel coupons before immersion into the simulated acidic environment and after immersion at the set period of experimental duration. In this experiment, the focus was to have four (4) time intervals –1 month, 3 months, 6 months and 12 months. The potential inhibition efficiency of the fish scale was then determined by using the below formula as illustrated by (Ebenso *et al.*, 2004; Omotosho *et al.,* 2012a; Omotosho *et al.,* 2012b):

$$IE = \frac{CR0 - CRin}{CR0} \times 100\% \quad (1)$$

Where: IE = inhibitor efficiency, CR_0 = Corrosion rate of sample in acid media without the inhibitor, CR_{in} = Corrosion rate of metal sample in the presence of the inhibitor
The surface coverage was determined from the expression in Equation 2 (Obot *et al.,* 2009):

$$Surface\ coverage = \frac{W0 - Win}{W0} \quad (2)$$

Where W_0 = Weight loss of metal sample in the control solution (solution without inhibitor), W_{in} = Weight loss of metal sample in solution with acid and inhibitor.

$$Corrosion\ rate\ (mmpy) = \frac{87.6\ W}{A \times T \times D} \quad (3)$$

Where W = weight loss in grams (g), T = immersion time in hours (hrs), A = Area of sample in centimetre squared (cm^2), D = Density of metal in gram per cubic centimetre g/cm^3, K= 87.6 is the constant of corrosion rate

3.4.1. Effect of simulated acid rain concentration

Four (4) distinct pH solutions were created. A pre- and post-immersion weight was taken for the coupons. At the end of each immersion duration, the data was recorded and examined. The best indicator of how the acidity of the solution affects the corrosion at each condition is evaluated by the weight loss, corrosion rate and computations for each specific conditions.

3.4.2. Effect of inhibitor concentration or amount

Fish scale extract of around 90 grams (g) was prepared as detailed in section 3.2 and stored in the sample vial. Different inhibitor dosages—2 grams, 3 grams, and 4 grams—were utilised for each acid environments. The mild steel coupons are weighed before and after immersion with and without the inhibitor, in order to calculate the rate of corrosion under each circumstance and then calculate the effectiveness of inhibition achieved. In the experiment, a blank solution without the fish scale inhibitor that mimicked acid rain was utilised as a control parameter.

3.4.3. Effect of immersion time

The coupons were submerged in each acid environment with varying inhibitor concentrations for a duration of 1, 3, 6, and 12 months. The coupons were removed from the environment, cleaned, and reweighed after each and every period. After the trial was complete, the collected data is evaluated to identify at what point the fish scale inhibitor was most effective. Lower weight loss results indicated that the inhibitor was working best during that duration.

3.4.4. Electrochemical measurements (short-term test)

The test was conducted using a model AUTOLAB PGSTAT 302N potentiostat and NOVA 1.11 software. The reference electrodes are saturated calomel electrodes (SCE) made of Ag/AgCl 3 mol/L KCl, while the counter electrode was platinum. The potentiodynamic polarisation measurements were analysed from the cathodic to the anodic direction during the experiments, which were conducted at a scan rate of 10 mVs-1. To derive corrosion current densities (I_{corr}), the linear Tafel part of the anodic and cathodic plots was extrapolated to determine corrosion potential. By applying the I_{corr} values acquired from equipment readout, the Tafel inhibition efficiency (IET%) was determined using the formula in Equation (4) as explained by (Abdel-Rehim *et al.*, 2011) and (Fouda *et al.,* 2013)

$$IE = \frac{Icorr - I'corr}{Icorr} \quad (4)$$

Where I_{corr} is the corrosion current density without the inhibitor, and I'_{corr} with the inhibitor.

3.5. Adsorption Isotherms

For varying inhibitor concentration at room temperature (ambient conditions), the adsorption isotherm was elucidated and the adsorption processes were constructed utilising the degree of surface covering (θ). In order to determine which adsorption isotherm best explained the interaction between the metal surface and the inhibitor based on the R^2 values of the various graphical plots, experimental data were fitted to a variety of isotherms. These include Langmuir (Foo & Hameed, 2010), Freundlich (Ajayi *et al.,* 2011),Temkin (Omotosho *et al.,* 2012a). Standard free energy of adsorption can be computed from values of adsorption equilibrium constants as follows:

$$\Delta G^{\circ}_{ads} = -RT \ln(55.5K_{ads}) \quad (5)$$

Where ΔG° is the standard free energy of adsorption and the value 55.5 represents the molar concentration of water in solution. Values of G°ads between -20 kJ.mol-1 and lower represent an electrostatic interaction between the charged adsorbent and charged substrate surfaces, while values between -40 kJ.mol-1 and above represent the sharing or transfer of an electron from the adsorbent molecules to the substrate surfaces, resulting in a coordinate type of bond. (Jmiai *et al.*, 2017).

3.6. Surface morphology analysis (SEM)

To assess the change in surface morphology brought on by contact with the test solutions and to monitor the effects of the addition of the inhibitor, the Scanning electron microscope JOEL JSM-7600F was used. The mild steel metal's surface profile was examined before and after corrosion in both the presence and absence of the inhibitor.

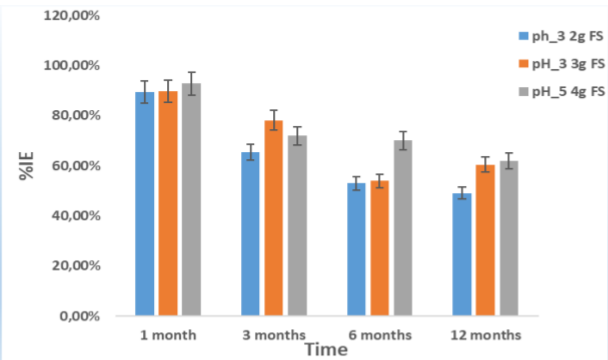
4. RESULTS AND DISCUSSION

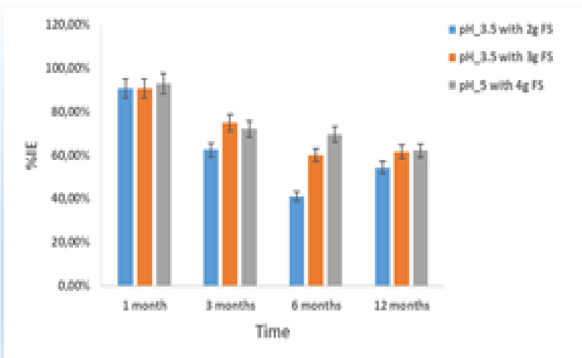
4.1. Effect of simulated acid rain concentration

Figure 2 shows that the weight loss was higher for coupons in a much more acidic environment which was at pH 3 and pH 3.5 as was expected. It was evident that the weight loss also gradually decreases as the fish scale inhibitor is added. It can be noted that the corrosion rate is the highest on the coupons that were immersed in the acidic solution with pH 3, 3.5 and pH 4 where the corrosion rates are noted to be slightly higher than the ones of pH 5 environment. The %inhibition efficiency increases as the acid environment decreases with pH 5 showing higher results illustrated by graphs in Figure 1.

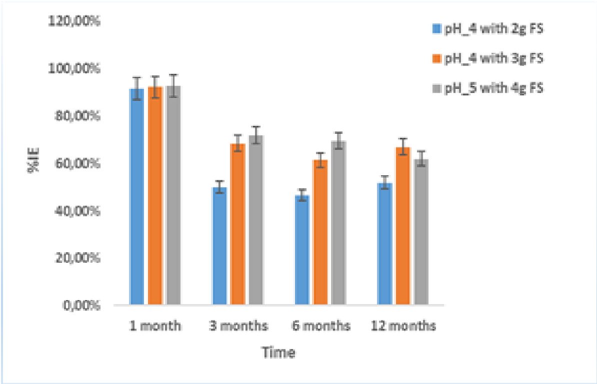
4.2. The effect of the inhibitor amount

The introduction of the fish scale (FS) inhibitor shows a substantial decrease in the weight loss and corrosion rate, i.e. the weight loss which is represented by the coupons that were immersed in the 1st 3 months without the fish scale inhibitor show a rapid increase in the corrosion rate than the coupons with the fish scale inhibitor. It can also be observed that the coupon with pH 5 and 4g FS inhibitor for the 1-month immersion in in Figure 1 has the highest %inhibition efficiency of 92.74%.





(a) *(b)*

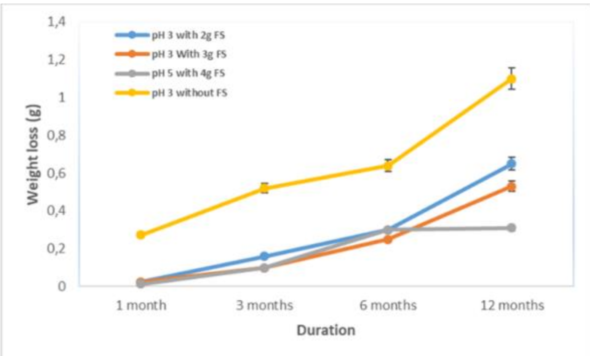


(c)

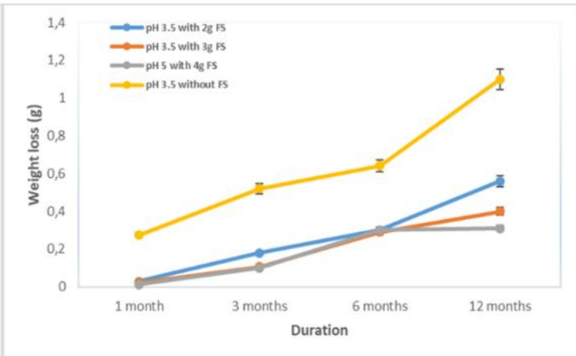
Figure 19: *Inhibition efficiency of mild steel (a) in a solution with pH 3 and 2&3 grams inhibitor (b) in a solution of pH 3.5 with 2&3 grams inhibitor (c) in a solution of pH 4 with 2&3 grams inhibitor. pH 5 with 4 grams is used to compare data for all 3 conditions.*

4.3. Effect of immersion time

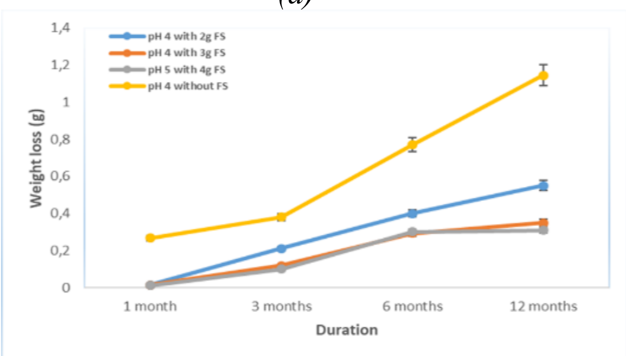
From the results below from Figure 2 it is evident that there is an increase in weight loss as the months goes towards the month's 12, which result in a decrease on inhibition efficiency. The inhibitor adsorption capacity declines the longer it is utilised in the corrosive acid environments.



(a)



(b)



(c)

Figure 20: *Weight loss for coupons without and with inhibitor – pH 5 with 4 grams as used to compare data (a) MS coupons in a solution of pH 3 with 2 & 3grams FS (b) MS coupons in a solution of pH 3.5 with 2 & 3 grams FS (c) MS coupons in a solution of pH 3.5 with 2 & 3 grams FS.*

4.4. Potentiodynamic Polarization Techniques

The Tafel plots show both the cathodic and anodic plots are influenced by the addition of the fish scale (FS) inhibitor as they both move away from the plot of the mild steel without the inhibitor. The decrease in values of both the anodic and cathodic Tafel slopes (I_{corr}) in Figure 3 with increase inhibitor amount shows that the addition if the inhibitor modifies the mechanism of the hydrogen reduction as well as decrease the rate of anodic dissolution in all cases. Table 3 illustrate the inhibition efficiency at each condition, with the highest percentage efficiency at 92.4% at pH 5 condition with 4g fish scale inhibitor.

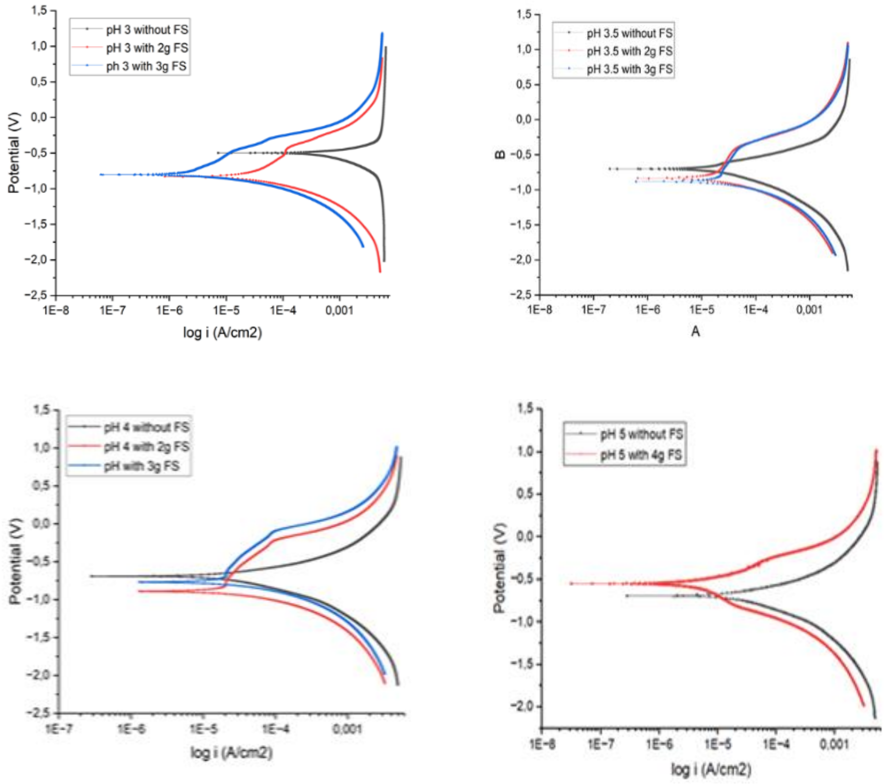


Figure 21: *Tafel plots for the mild steel in simulated acid rain solution with and without the fish scale inhibitor*

Table 3: *Potentiodynamic polarization %IE of the mild steel in different acidic environment with 3g, pH 5 with 4g is used to compare data*

PH	Inhibitor amount(g)	I_{corr} (A) Blank	I_{corr}(A) With FS	%IE	Inhibitor amount(g)	I_{corr} (A) Blank	I_{corr}(A)	%IE
3	2	1,785E-06	4,228E-07	76,38	3	7,985E-05	1,091E-05	87.0
3.5	2	1,268E-05	2,211E-06	82,57	3	0,0003721	4,102E-05	89.0
4	2	2,084E-05	1,831E-06	91.85	3	2,3E-05	2,345E-06	90.2
5	4	2,38E-05	1,831E-06	92.4	4	2,38E-05	1,831E-06	92.4

4.5. Adsorption isotherms

The plots of different isotherms models, including Langmuir, Freundlich and Frumkin, were used to obtain correlation coefficients, which were then used to identify the isotherms that applied to experimental data the most. Langmuir isotherm exhibited the best results of R^2 close to unity as indicated in Table 4 and will be the point of focus. These values are significant because they can be used to determine how strongly fish scale molecules interact with mild steel surfaces. When the adsorption equilibrium constants have high values, an efficient adsorption process frequently leads to higher inhibition efficiency.

Table 4: *Correlation coefficient of different adsorption isotherms – Langmuir, Frumkin and Freundlich at different pH concentration of the simulates acid solution.*

Duration per pH	Correlation coefficient R^2		
	Langmuir log((C/θ)/C)	Frumkin log(θ/1-θ)/C	Freundlich log(θ/C)
ph3_3months	0,79	0,60	0,37
ph3_6months	0,94	0,80	0,51
ph3_12months	0,89	0,94	0,79
ph3_1months	0,99	0,78	0,83
ph3.5_3months	0,80	-	-
ph3.5_6months	0,70	0,99	0,96
ph3.5_12months	0,98	0,94	0,73
ph3.5_1months	0,99	0,94	0,84
ph4_3months	0,69	0,16	0,55
ph4_6months	0,94	0,99	0,65
ph4_12months	0,71	0,46	0,98
ph4_1months	0,99	0,89	0,99

The negative nature of the values of $G°_{ads}$ shown in Table 5 indicates spontaneity of the adsorption process and the stability of the adsorbed film on the surface of mild steel according to Langmuir adsorption isotherm.

4.6. SEM analysis

Figure 4 shows SEM results for the coupon before immersion as the 'blank' sample. Figure 5 shows coupons that were immersed in an acidic solution with pH 3 without the FS inhibitor for 3 months, 6 months and 12 months respectively. The coupon that was immersed for 12 months shows a rougher texture than the rest as corrosion has taken place over the longest duration. Figure 6 shows coupons that were immersed with 2g inhibitor. Observations revealed that the surface is smoother than that of Figure 5 which is an indication that though corrosion has occurred on the mild steel coupons, the fish scales did form a protective layer on the surface of the coupon slowing down the corrosion rate.

Table 5: *Thermodynamic and adsorption parameters (Langmuir adsorption isotherm) for mild steel in simulated acid rain solution with FS inhibitor.*

Duration per pH	R^2	Intercept	q_{max}	Slope	K_{ads} (M^{-1})	G_{ads} (kJ/mol)
pH3_3months	0,792	0,590	1,695	0,630	0,937	-9,619
pH3_6months	0,940	0,588	1,701	0,650	0,905	-9,535
pH3_12months	0,890	0,300	3,333	0,860	0,349	-7,215
pH3_1months	0,999	0,100	10,000	0,948	0,105	-4,303
pH3.5_3months	0,800	0,375	2,667	0,756	0,496	-8,072
pH3.5_6months	0,700	0,012	83,333	0,300	0,040	-1,942
ph3.5_12months	0,980	0,430	2,326	0,800	0,538	-8,268
ph3.5_1months	0,999	0,100	10,000	0,940	0,106	-4,323
ph4_3months	0,694	0,230	4,348	0,990	0,232	-6,225
ph4_6months	0,936	0,820	1,220	0,404	2,030	-11,503
ph4_12months	0,706	0,498	2,008	0,715	0,697	-8,899
ph4_1months	0,999	0,092	10,870	0,949	0,097	-4,097

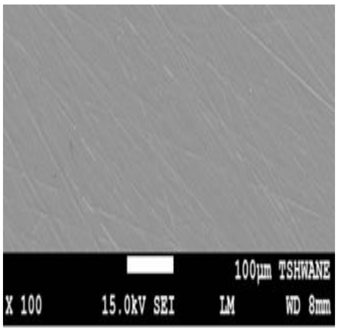
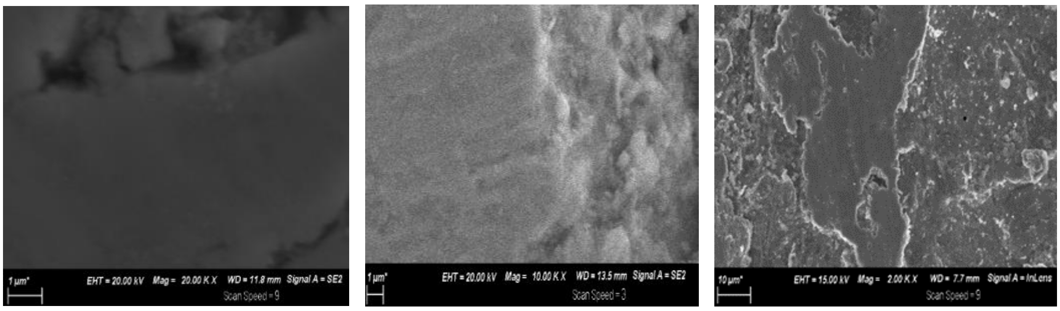
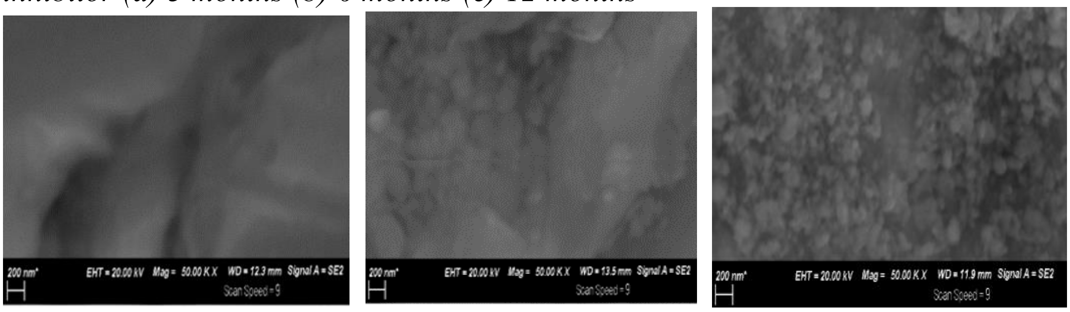


Figure 4: *MS coupon before immersions*



(a) (b) (c)

Figure 5: *Mild steel coupon after immersion in acidic solution with pH 3 without FS inhibitor (a) 3 months (b) 6 months (c) 12 months*



(a) (b) (c)

Figure 6: *Mild steel coupon after immersion in acidic solution with pH 3 with 2g FS inhibitor (a) 3 months (b) 6 months (c) 12 months*

5. CONCLUSION

The long-term coupon test has demonstrated that utilising fish scales as an inhibitor was successful, with the maximum inhibition efficiency coming in at 92.74%. When Tafel plots were constructed to depict the behaviour on the anodic and cathodic side of the mild steel coupon with a greatest inhibition efficiency of 92.4%. Therefore, the short-term coupon tests, also known as electrochemical investigations, indicated a positive outcome. The adsorption isotherm that best fitted/gave good results was found to be the Langmuir isotherms with the R^2 results a favourable adsorption points. The calculated energy G̊, exhibited negative energy results which is an indication that the reaction between the FS inhibitor and mild steel surface is spontaneous. The metal surface studies from the SEM analysis also show the positive outcome confirming that a film formed on the coupons surface is an indication that the fish scales molecules are being adsorbed as they interact with the steel samples over time. This is observation support graphs in Figure 1, 2 and 3.

Future work
Future work may include the study of the inorganic and organic part of the fish scale molecule separately as corrosion inhibitors. Furthermore, a different solution can be used, ie. A saline solution, in order to get a fair representation and reliabity of the use of fish scales as a corrosion inhibitor while also exploring their applications on the metal surface.

Author Contributions:. Conceptualization, NF Nyambi and K Premlall; methodology, NF Nyambi; validation, NF Nyambi and K Premlall; formal analysis, NF Nyambi.; investigation, NF Nyambi; resources, K Premlall; data curation, NF Nyambi.; writing—original draft preparation, NF Nyambi; writing—review and editing, NF Nyambi and K Premlall; visualization, NF Nyambi.; supervision, K Premlall; project administration, NF Nyambi and K Premlall.; funding acquisition, K Premlall.

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