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GREEN OPERATIONS INITIATIVES IN THE FORMAL BRICK MANUFACTURING INDUSTRY: A CASE STUDY OF VHEMBE DISTRICT, SOUTH AFRICA

Tolulope Elizabeth Aniyikaiye
Walter Sisulu University

Abstract:
The growing global emphasis on sustainable industrial practices has catalyzed the transformation of traditional manufacturing sectors, including brick production. This study explores the integration of green operational practices within a formal brick manufacturing company in South Africa, highlighting its potential contribution to sustainable industrial development and principles of the circular economy. A qualitative case study approach was employed using field visits, semi-structured interviews with key personnel at FMB Bricks Ltd, and direct assessment of production activities to identify environmentally sustainable practices. The data collected were analysed thematically, revealing core sustainability initiatives such as enhanced material efficiency, internal reuse of kiln ash and broken bricks, dust and emissions control, and energy optimisation. These practices reduce environmental impact and align with circular economy strategies by promoting resource recovery and minimising waste. Despite these advances, notable challenges persist, including the plant's vulnerability to power outages, resulting in continued reliance on energy-intensive clamp kilns, and the absence of an air quality monitoring system. To strengthen environmental performance, the study recommends gradually shifting toward renewable energy sources and adopting real-time environmental monitoring technologies. The findings suggest that with strategic investment and policy support, formal brick manufacturers can serve as catalysts for low-carbon, circular, and resilient industrial development.

Key words: brick manufacturing industry, circular economy, energy optimisation, environmentally sustainable practices, material efficiency

INTRODUCTION

The global demand for environmentally sustainable construction materials continues to grow as countries seek to lessen the carbon footprint of the built environment [1]. Fired clay bricks remain one of the most widely used building materials, particularly in developing economies [2]. However, conventional brick production methods contribute significantly to environmental degradation through excessive resource extraction, inefficient energy use, and high emissions of greenhouse gases and particulate matter [3, 4, 5]. In many regions, traditional kilns, such as clamp kilns, scove, scotch, and Fixed Chimney Bull's Trench Kilns (FCBTKs), dominate brick production despite relying on low-grade fuels and outdated technologies, thereby worsening air quality and accelerating climate change [6, 7].

Given the urgency to decarbonize the construction sector in line with mid-century net-zero emission targets, there is a pressing need to develop sustainable alternatives for producing building materials [2]. Circular economy principles are increasingly recognized as a viable pathway for reducing embodied carbon in the construction industry. The National Waste Management Strategy (NWMS) 2020 in South Africa articulates the concept of a circular economy as one that seeks to close the loop between resource extraction and waste disposal [8]. It advocates for resource conservation through waste prevention, reuse, recycling, and recovery, thereby minimizing the extraction of virgin materials and reducing environmental pollution. In the context of construction, circular economy interventions can take various forms, ranging from enhanced material efficiency and the adoption of green innovative technologies to improved waste management practices and regulatory reforms [2]. These interventions support environmental and economic sustainability by reducing production costs, minimizing waste, and incentivizing innovation. Notably, industrial symbiosis, whereby waste from one production process becomes the input for another, is one such innovative strategy that can reduce resource intensity in industrial operations [8]. The application of circular economy principles within the construction industry offers multiple pathways to sustainability, including industrial symbiosis, energy recovery, and material reuse [9].

Green innovation in brick manufacturing is critical to improving energy performance and minimizing dependence on fossil fuels [10]. According to global estimates, the building and construction sector accounted for approximately 32% of total energy use in 2023 [1]. Enhancing energy efficiency through technological innovation in production processes is vital for achieving national and international climate commitments, including the Sustainable Development Goals (SDGs) and the Paris Agreement. In addition to direct environmental benefits, green innovation also delivers socio-economic gains such as improved public health, reduced ecological liability, enhanced worker safety, stronger relationships with regulatory authorities, and greater market competitiveness [11].

In South Africa, the emergence of formal brick manufacturing facilities characterized by large-scale, automated production lines and regulated environmental controls presents new opportunities for greening the brick industry [12]. These formal operations are particularly concentrated in urban and peri-urban areas, where environmental enforcement mechanisms are more robust [13]. The South African government, in alignment with its zero-pollution objectives, is actively promoting practices such as waste minimization, effective waste services, and environmental compliance as part of its broader sustainability agenda [8].

Despite these positive developments, academic attention to green practices in South Africa's formal brick sector remains limited. This study investigates a formal brick manufacturing facility in Vhembe District, South Africa, which has integrated several green initiatives into its operations. While there are approximately 112 industrialised brick plants across South Africa [14], only two operate in Vhembe, and one was selected for this case study. By evaluating its energy practices, material choices, and waste reduction strategies, the study seeks to document and analyse how green operational models can be practically implemented within the brickmaking sector and replicated across similar contexts.

LITERATURE REVIEW

Clay brick remains a preferred construction material due to its durability and load-bearing properties [15, 16]. The rise in global population and the resulting demand for housing have increased the scale of brick production, which is currently approximately 1.5 trillion bricks annually [17]. Yet, the industry is predominantly informal in developing countries, relying on outdated techniques and high-emission fuels such as coal and biomass [18]. The brickmaking industry accounts for around 2.7% of carbon and 20% of black carbon emissions globally [18, 19].

Beyond carbon emissions, brickmaking contributes to environmental degradation through the unlawful excavation of fertile topsoil. According to Carson [20], removing just one millimetre of topsoil can lead to the depletion of approximately 10 kg/ha of nitrogen, 7 kg/ha of phosphorus, and 15 kg/ha of potassium. To curb the ongoing loss of arable land and mitigate the ecological impacts of brick production, it is essential to partially or fully substitute soil with cheap, value-added alternative materials. In this context, researchers have examined the incorporation of agro-industrial residues such as sugarcane bagasse ash, rice husk ash, cocoa shell, and tea waste into brick matrices and their effects on the physical and mechanical performance of fired bricks [21, 22, 23, 24]. These studies revealed that at substitution rates up to 5% by weight, the resulting bricks were lighter, exhibited higher water absorption, and showed reduced compressive and flexural strength. However, the bricks still conformed to the minimum statutory standards for masonry applications. On the other hand, additions like grape and cherry seed waste at 5% inclusion rate have been shown to enhance mechanical strength, while sugarcane ash has proven effective in reducing shrinkage during firing [25]. Facilitating the transition from traditional to sustainable brickmaking practices requires coordinated efforts at the local, national, and global levels. Given the large volumes of fly ash generated worldwide, several countries have implemented policies to promote its reuse. India, for example, has introduced legislation mandating the inclusion of at least 25% fly ash in brick production, to reduce soil depletion and encourage industrial waste valorisation [18].

Clay brick production typically involves firing at extremely high temperatures, often reaching up to 1400°C, which requires substantial fuel input and results in significant emissions of air pollutants that pose risks to human health [16]. As such, transitioning to more energy-efficient firing technologies is essential. A study by Bashir et al. [26] using Open LCA software (v1.10.3) and the Eco-invent database, compared the energy efficiency and emission profiles of a modern zigzag kiln (ZZK) with a traditional (FCBTK). The results showed that the ZZK offered a 30% reduction in energy consumption and achieved substantial reductions in emissions: 80% for black carbon, 30% for CO_2, and 35% for $PM_{2.5}$. The environmental impact was further mitigated by a 95% decrease in terrestrial acidification, 93% in photochemical oxidant formation, and 63% in particulate matter formation when using ZZK technology. Additional studies have reported energy savings ranging from 30% to 70% when clamp kilns are replaced with Vertical Shaft Brick Kilns (VSBKs), reinforcing the case for modernisation [27, 28, 29]. Furthermore, Lissy et al. [16] demonstrated that integrating industrial residues into clay matrices could lower the required firing temperature to approximately 600 °C, reducing costs and emissions. In their study, a mix ratio of Cement: Red Earth: Sand: Glass Powder: Quarry Dust = 4:1:1:1.5:2.5, when fired at 600°C, yielded bricks that met the minimum statutory requirements for masonry units.

In the South African context, Lloyd [30] evaluated the energy performance of various kilns used by medium-scale brick manufacturers and identified the VSBK as the most energy-efficient, requiring just 1 MJ/kg of fired bricks compared to 7 MJ/kg for clamp kilns. For large-scale production exceeding 30 million bricks per annum, Lloyd [30] recommended the tunnel kiln, which has a moderate energy requirement of 2 MJ/kg, as a more viable and sustainable option.

METHOD

The study area description

This study was limited to FMB Bricks Ltd (the trade name is withheld for confidentiality reasons), one of the major clay brick producers in South Africa (Fig. 1).

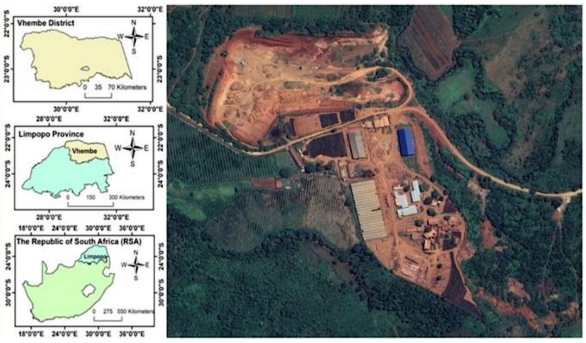

Fig. 1 The study area map

The FMB Bricks Ltd is situated at the outskirts of Thohoyandou along Mapate Road, Vhembe District. It is located at geographical coordinates 23.004353S and 30.388383E, in a rural area surrounded by arable land. The company manufactures fired clay bricks on a large scale. FMB Bricks Ltd obtains clay from its mine located about 500 meters away from the factory site. Coal is the primary fuel for brick firing, sourced locally and from Botswana.

METHODOLOGY

The study employed a qualitative case study approach to investigate the environmentally sustainable practices of a formal brick manufacturing facility in South Africa. The study was conducted between December 2021 and February 2022. FMB Brick Ltd was selected based on its fully automated operation and proven level of dedication to environmental compliance. This approach facilitated a comprehensive and context-specific understanding of formal brick manufacturing industry activities. Primary data were collected via semi-structured interviews with key role players, including the production manager and factory supervisors. The interview questions covered the company's operational procedures, innovations implemented for sustainability, and challenges. Interviews were complemented with in-situ field observations across key production areas, ranging from clay extraction to kiln and packaging sections, to understand the production procedures and environmental control measures. Additionally, secondary data, such as the brick production records, were examined from March 2021 to February 2022. Using a coding technique, thematic content analysis was implemented, integrating inductive themes that surfaced from the data. This analytical strategy enabled the identification of both best practices and operational gaps.

RESULTS AND DISCUSSION

Workforce Structure and Operational Overview of FMB Bricks Ltd

FMB Bricks Ltd operates as a fully automated brick manufacturing facility with 201 employees, comprising 38% men and 62% women. The vast majority of employees, approximately 95.5% are within the working-age bracket of 18 to 60 years, while only 0.5% are older than 60. Most employees are directly involved in brick handling and production, whereas only about 3.5% are assigned administrative roles. The company manufactures various clay-based products, including standard clay bricks, hollow bricks, and half clay blocks. Although standard bricks constitute the primary output, hollow bricks and half blocks are produced upon customer request. FMB Bricks Ltd has three brick-making lines, three crushing plants, and a Vertical Shaft Brick Kiln (VSBK), reflecting its commitment to high-volume, mechanized production. The plant draws on three primary energy sources: electricity, diesel-powered generators, and coal. While electricity powers the automated systems, generators provide backup for the workshop and office spaces during outages. Coal remains the dominant fuel for the brick-firing process.

Production phases

Brick production in FMB Bricks Ltd. is subdivided into five main processes: mining, milling, molding, drying, and firing (Fig. 2).

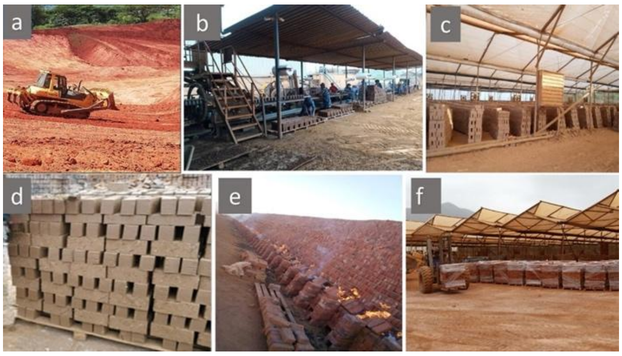

Fig. 2 Brick manufacturing process photographs taken during site survey: a – mining site, b – cross-sectional view of the moulding section, c – drying shelf which uses electric-powered industrial fans, d – air drying of bricks, e – clamp kiln, f – packing of bricks for sales

Mining: Brick making begins with the mining stage. Mining involves the excavation of land for clay soil. In FMB Bricks Ltd, excavation is carried out using the excavator and bulldozer. According to the factory manager, the topsoil from the surface down to a depth of approximately 1.5 to 4 metres is removed and separated before excavating the underlying clay soil. Once the clay is exposed, it undergoes an **initial blending phase** in which the **damaged dried bricks and ash generated during brick firing** are incorporated into the raw clay. The prepared clay is mixed with **sand and duff** with a standard mixing ratio of **25 parts clay to 1 part sand and 1 part duff**. Sand acts as a tempering agent, reducing plasticity and shrinkage, and aids the fast drying of the brick [27]. On the other hand, the duff serves as an internal fuel source that supports energy efficiency during firing [31]. The clay mixture is then loaded into the front-end loader and transported to the milling section.

Milling: The milling section of the FMB Brick Ltd is an automated system in which the clay material conveyed by the front-end loader is crushed into a finer texture before transfer for brick making. The feeder box receives the clay soil from the front-end loader and transfers it to the crusher, which comprises hammers for breaking stones and soil lumps. After this, the crushed soil materials are transported via the conveyor belt to the screen. The screen consists of a metallic mesh of small diameter, which sieves out small stones from the soil, allowing the passage of fine-textured soil particles. The fine-textured soil (material stockpile) is then transferred via the conveyor belt to the feeder box while the small stones are returned to the crusher for further breaking (Fig. 3).

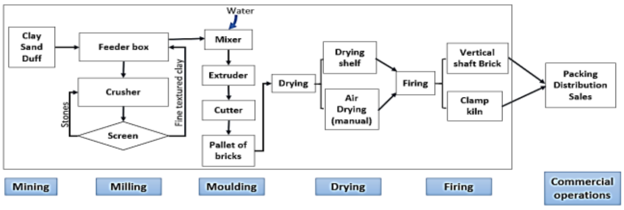

Fig. 3 Brick production process flowchart

Molding: The molding stage in the FMB Bricks Ltd. is automated. Material stockpile collected by the frontend loader is transferred into the mixer. Water is pumped into the mixer simultaneously, while the rotor spins and mixes the supplied clay soil with water. The homogeneous wet soil mixture moves to the extruder, transforming into a loaf. Through the conveyor belt, the loaf is transferred to the cutter, which consists of wired gauze for cutting the loaf into small, specified brick sizes and shapes. As the formed bricks are continuously transported on the conveyor belt, defective bricks are automatically removed, while the undefective green bricks are collected by workers and arranged transversely on pallets.

Drying: Drying involves the removal of water molecules from the wet bricks. Drying of bricks in FMB Bricks Ltd is a function of electricity availability, seasons, and meteorological factors. In an uninterrupted electricity supply, bricks are dried on the drying shelf using electric-powered industrial fans. Based on the interview with the factory supervisor, wet bricks on the drying shelf get dried within 4 weeks. Bricks could also be dried naturally through air drying. Air drying is a process whereby pallets of wet bricks are exposed to meteorological conditions, especially wind and sunlight, to dry naturally. Bricks are mainly dried in FMB Bricks Ltd by air drying. It has been reported that natural drying is the preferred method of brick drying by the majority of South African Brick manufacturers due to its non-reliance on fuel [6, 14]. Drying of wet bricks subjected to air drying depends on seasons and meteorological factors. According to the factory manager, wet bricks dry faster (within 2 to 3 weeks) during spring (September-November) than in other seasons of the year, due to fast-blowing wind. During winter and summer, bricks get dried within 6-8 weeks and 4-5 weeks, respectively. Another factor determining the drying time of bricks is the type of bricks produced. Hollow bricks were reported to dry relatively faster than the other brick types.

Firing stage: Both the VSBK and Clamp Kiln are used for brick firing. The VSBK is a modern, energy-efficient technology comprising a permanent, weatherproof structure of rectangular blocks called "shafts," in which bricks are fired. Field measurements indicate that each shaft is 5.2 m high and has a 1.4 m × 1.4 m surface area. Seven shafts were reported to be functional, according to the factory supervisor. The VSBK comprises a loading section, a firing section, and an unloading section. A temperature reader, which displays the temperature in each shaft section, was also noted during the fieldwork. The dried bricks are loaded from the top of the shaft, moving slowly down to the centre (the firing zone) with the highest temperature. Heat transfers between the flue gas from the combustion zone and the incoming bricks as the dried bricks move to the centre. The dried bricks are preheated, while the temperature of the exiting flue gas drops [32]. From the observation noted during the field survey, the maximum temperatures of the VSBK range between 650 and 725°C, but they are usually regulated to about 600°C to prevent over-burning of the bricks. According to the production manager, 45 g of coal per brick is used for brick firing in the VSBK. In addition, the factory supervisor reported that the VSBK operates continuously for 49 weeks annually, with the final 3 weeks reserved for servicing and maintenance.

A clamp kiln is an outdated, energy-inefficient technology comprising a temporary pyramidal structure of dried unfired bricks used as an oven for baking bricks [31]. The clamp kiln is roofless; its operation depends on meteorological conditions. In South Africa, the clamp kiln is the most commonly used firing technology for brick production, typically operated on a commercial or small scale by formal or informal enterprises, respectively. [14]. According to the factory manager, clamp kilns are often constructed in 4 locations within FMB Bricks Ltd. Each clamp kiln is built with 400,000 to 2,000,000 green bricks, depending on the availability of dried bricks and the meteorological conditions. Layers of dried unfired bricks are continuously created until the desired height is achieved. Clamp kiln is an inefficient firing technology since the heat in the hot flue gases, fired bricks, and the clamp kiln arrangement is lost after each batch of brick is fired [31]. Based on information gathered during the field survey, firing in the clamp kiln requires about 120 g of coal per brick and takes 7 to 12 days.

Productivity level

The brick production record shows peak production in July 2021 and the lowest in December 2021. The reduced production was due to the total shutdown of the factory for 3 weeks at the end of the year. According to the factory manager, the same quantity of bricks was produced daily by the VSBK; hence, an almost equal monthly production rate was reported for the one-year record collected, except in December 2021, due to the end-of-year break. In the case of the clamp kiln, production was generally high from May 2021 to November 2021. This could be partly due to favourable weather conditions for the firing of the clamp kiln and high demand for bricks. A low level of brick production was observed with the clamp kiln in summer

(December 2021-February 2022), probably due to the end-of-year break and the unfavourable meteorological conditions, which could have hindered the clamp kiln operation. Findings from the study have shown that, on average, 2.8±0.9 million bricks were produced monthly in the FMB Bricks Ltd using the clamp kiln, while the monthly mean production for the VSBK is 0.8±0.2 million bricks. Figure 4 shows the monthly brick production via the clamp kiln and VSBK at FMB Bricks Ltd. from March 2021 to February 2022.

Green initiatives observed

The case study revealed several noteworthy green initiatives. The green innovations utilised in various sections of FMB Bricks Ltd and their implications are highlighted in Table 1.

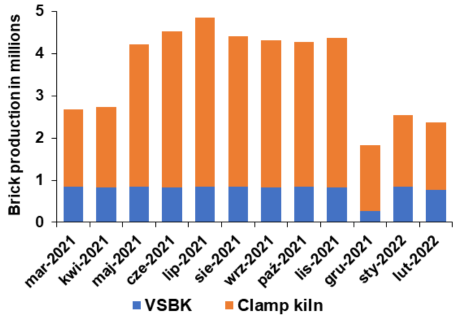

Fig. 4 Brick production rate at the FMB Bricks Ltd

N.B: VSBK (Vertical Shaft Brick Kiln) is the modern energy-efficient technology used for brick firing at FMB Bricks Ltd Clamp kiln is an outdated and energy-inefficient brick firing technology employed by FMB Bricks Ltd.

Table 1
The green innovative approaches utilised in various sections of FMB Bricks Ltd

	Section	Strength	Effects
1	Mining	The inclusion of damaged dried bricks in raw clay during the mining stage	Reuse of broken, dried bricks
		Location of the mining site outside the company	Minimises dust emission within the factory premises
		The inclusion of previously generated fly ash in the clay mixture	Reuse of fly ash, which minimizes carbon emissions and virgin raw material use.
		Incorporating duff into raw clay during the mining stage	Enhances pore formation in fired bricks. The duff also serves as the internal energy of the brick, supplementing coal combustion and improving energy efficiency during brick firing. The duff reduces the overall fuel use.
2	Milling	Crushing, grinding, and sieving of the soil mixture before molding	This minimises cracking and damage in bricks.
		Modern brickmaking plant with an automated feeder box	This handles various materials and provides a consistent feed, thus enhancing efficiency and reducing labor costs.
		The use of fired broken bricks to dry and re-open the orifices of the screen during wet seasons	This is a means of recycling and reusing broken fired bricks.
3	Stockpile section	The presence of shed over the stockpile	The shed serves as a protective covering for the stockpile against wind erosion, thereby reducing dust emissions.
4	Molding	Spreading of net on each layer of wet bricks arranged on the pallet	The net prevents the wet bricks from slipping during transportation to the drying site.
5	Drying	The use of the air-drying method	Bricks are dried naturally without relying on fuel
6	Firing	The use of the Vertical Shaft Brick kiln (VSBK)	- Reduced coal consumption - Enhanced energy efficiency due to heat exchange between the air/gas and bricks - The firing temperature could be regulated, thus minimising over-burning of bricks. - Faster rate of brick firing compared to the clamp kiln. - VSBK occupies less space compared to the clamp kiln
7	Packing unit	Over-burnt bricks, often called clinkers, are sold to customers at a relatively cheaper rate than the standard bricks.	Wastage is prevented
8	Others	Wetting of unpaved roads within and outside the company twice daily	This is a dust emission control measure that improves air quality within the factory and surrounding communities.
		The company is located over 1 km away from residential areas. It is recommended that brick kilns be located 0.8 to 3 km from residential areas, schools, hospitals, government's reserve forests, and public buildings [33, 34].	The impact of the activities of FMB Bricks Ltd in terms of noise and air quality is not felt in the residential environment.
		The company site has trees planted within it and is surrounded by natural vegetation.	Trees improve the air quality of the company environment by filtering pollutants and particulate matter from the air, absorbing carbon dioxide, and releasing oxygen [35]. Trees also act as natural sound barriers, reducing noise pollution generated from industrial activities.

The green practices illustrate the compliance-oriented approach adopted by FMB Bricks Ltd. These initiatives align with South Africa's National Environmental Management Act (NEMA) and resonate with broader global sustainability frameworks such as the United Nations Sustainable Development Goals (SDGs). Importantly, the green transition in this plant was supported by strategic investment in technology, capacity building, and leadership commitment to sustainability.

LIMITATIONS AND RECOMMENDATIONS

One of the notable operational challenges observed at FMB Bricks Ltd is the vulnerability of the production process to power outages. These interruptions disrupt the operation of automated systems and increase dependence on traditional clamp kilns, which are less energy-efficient and environmentally unsustainable. This reliance counteracts efforts to modernize production and reduce emissions. A phased transition toward renewable energy sources such as solar or wind should be prioritised to enhance resilience and ensure uninterrupted operations. Integrating such systems would reduce reliance on the national grid while aligning the factory's operations with sustainability goals.

Another critical limitation identified during the fieldwork is the **absence of an air quality monitoring system** within the production facility. The lack of real-time environmental data limits the company's ability to assess and manage air pollutant emissions effectively. This gap poses risks to environmental compliance, worker health, and community well-being. Therefore, FMB Bricks Ltd should invest in **low-cost air quality sensors** or develop partnerships with environmental agencies to establish a reliable monitoring framework. Doing so would support regulatory alignment, enhance transparency, and contribute to a culture of continuous environmental improvement.

Addressing these limitations through strategic investment and proactive management can significantly improve the plant's environmental performance and position it as a leader in sustainable brick manufacturing.

CONCLUSION

The case study highlights the capacity of South Africa's formal brick manufacturing sector to contribute meaningfully to sustainability through the adoption of environmentally sustainable practices. Several green initiatives were identified, including enhanced material utilisation, effective dust and emissions management, and improved energy efficiency within the selected brick production facility. These measures present a replicable framework for other brick manufacturing facilities within the industrial sectors striving toward decarbonisation and reduced environmental footprints. Brick manufacturers can substantially minimize environmental impact by embracing advanced technologies and implementing comprehensive environmental management strategies. To support this transition, policymakers and industry leaders must prioritise and invest in such initiatives as part of a broader agenda for sustainable industrial progress.

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Tolulope Elizabeth Aniyikaiye
ORCID ID: 0000-0001-5316-4015
Department of Civil Engineering
Faculty of Engineering, Built Environment
and Information Technology
Walter Sisulu University, Buffalo City Campus
College Street Site, Private Bag X1421, East London, 5201
Eastern Cape, South Africa
e-mail: taniyikaiye@wsu.ac.za