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Review article

Addressing the water-energy nexus: A focus on the barriers and potentials of harnessing wastewater treatment processes for biogas production in Sub Saharan Africa

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ABSTRACT

Several anthropogenic activities reduce the supply of freshwater to living organisms in all ecological systems, particularly the human population. Organic matter in derived wastewater can be converted into potential energy, such as biogas (methane), through microbial transformation during anaerobic digestion (AD). To address the current lack of data and values for wastewater generation in Sub-Saharan Africa, this review analyzes and estimates (at 50% and 90% conversion rates) the potential amount of wastewater-related sludge that can be generated from domestic freshwater withdrawals using the most recent update in 2017 from the World Bank repository and database on freshwater status in Sub-Saharan Africa. The Democratic Republic of the Congo (DRC) could potentially produce the highest estimate of biogas in Sub-Saharan Africa from domestic wastewater sludge of approximately 90 billion m^3, which could be converted to 178 million MWh of electricity annually, based on this extrapolation at 50% conversion rates. Using same conversion rates estimates, at least nine other countries, including Guinea, Liberia, Nigeria, Sierra Leone, Angola, Cameroon, Central African Republic, Gabon, and Congo Republic, could potentially produce biogas in the range of 1–20 billion m^3. These estimates show how much energy could be extracted from wastewater treatment plants in Sub-Saharan Africa. AD process to produce biogas and energy harvesting are essential supplementary operations for Sub-Saharan African wastewater treatment plants. This approach could potentially solve the problem of data scarcity because these values for Freshwater withdrawals are readily available in the database could be used for estimation and projections towards infrastructure development and energy production planning. The review also highlights the possibilities for energy generation from wastewater treatment facilities towards wastewater management, clean energy, water, and sanitation sustainability, demonstrating the interconnections and actualization of the various related UN Sustainable Development Goals.

1. Introduction

The need for water for life's sustenance in all living organisms is existential and unarguable. Humans also use potable water extensively for agricultural, household, and industrial purposes. Yet, surface fresh water used extensively by all humans and other living things in all habitats accounts for less than 1% of the total water found on Earth. Although water covers about 75% of the earth's surface, 96.5 % of it is unusable due to excessive salt and mineral concentrations (sea and ocean). 3% is locked in ice caps and groundwater (Mishra and Dubey, 2015).

Water use is associated with the evolving concept of hygiene and sanitation, as well as diseases and epidemics, notably in sewage and water treatment. This understanding dates back at least three centuries (Salgot and Folch, 2018). Globally, increased amounts of raw sewage, agricultural run-off, and industrial effluent discharge have degraded

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water quality and contaminated the earth's surface water reserves. According to a United Nations (UN) Water Quality and Wastewater report, 1.8 billion people worldwide drink water contaminated by feces since up to 80% of wastewater is returned to the environment without being treated but reused unintentionally through dilution (UN, 2018). As a result, people and communities are exposed to water-borne pathogens such as cholera, typhoid, shigellosis and polio. Furthermore, water scarcity as a result of inadvertent misuse of water resources, combined with deterioration of water quality, is one of the most serious challenges facing arid and semi-arid nations (Adewumi et al., 2010; Roccaro and Verlicchi, 2018; Prüss-Ustün et al., 2019).

In recent years, we have confronted additional abiotic threats to potable water, such as xenobiotic or persistent organic contaminants (POPs). The vast majority of these POPs are byproducts of anthropogenic activities connected with daily life. These POPs are discharged into natural bodies of water and eventually find their way into various food chains. Previously, the most frequently mentioned POPs were antibiotics and the resulting global development of antibiotic resistance in animals and humans (Founou et al., 2016). However, Silva et al. (2021) demonstrate that ibuprofen and sulfamethoxazole contained in sewage sludge can accumulate in agricultural plant tissues when employed as a fertilizer, posing a new concern to human and animal consumption.

A number of POPs have been shown to accumulate in higher biotic levels, causing physiological and toxicological consequences in larger species in these food webs. Eventually, animals and humans develop diseases connected to hazardous substances and POP bioaccumulation. The World Health Organization (2016) and the United States Environmental Protection Agency (2020) have found that dioxins, such as 2,3,7, 8-Tetrachlorodibenzo-p-dioxin (TCDD), can impact cell differentiation of pregnant female mammary glands, with cascade effects on lactation. Recent research shows that the effects are not confined to pregnant female rats, but affect both male and female rodents (Vorderstrasse et al., 2004; Filgo et al., 2016). In addition, Ye et al. (2018) found that among 677 children exposed to TCDD during pregnancy, 14.5% had eczema, 22.5% had asthma, and 36% had hay fever. These disorders are persistent and might be difficult to treat medically. Also, active pharmaceutical compounds produced by humans and animals can potentially undergo further biochemical transformations with interactions with diverse microbial enzymes found in these waste streams, leading to the generation of poisonous chemicals harmful to ecological systems. Ingestion of recycled water containing persistent chemical endocrine disruptors has recently been linked to human harm. When such pollutants are present, removal in order to achieve recycled potable water frequently necessitates additional treatment steps and additional costs. Examples of such additional treatment steps include reverse osmosis treatment, ozonation, UV irradiation, photolysis, peroxidation (peroxide and UV), and ultrasound. Unfortunately, Vergili et al. (2019) have recently discovered carbamazepine in municipal wastewater. This compound is known to cause defects in neurological development and has also been linked to the inhibition of normal algae growth. Furthermore, this compound causes death in water flea species and even larvae of zebra fish (Hai et al., 2018).

From agricultural activities, increased levels of pollutants including nitrates and phosphates enter water bodies as runoffs, causing eutrophication, algae blooms, and a loss in water quality that further reduces potable water availability (Englande et al., 2015; Dereszewska and Cytawa, 2016). In other instances, high-level fertilizers leak into groundwater, lowering its quality (Sahoo et al., 2016). Continued consumption of high concentrations of nitrates and nitrites in water can cause cancer and diabetes (Parvizishad et al., 2017). Commercial farming of pigs produces large quantities of urine containing ammonia that is very detrimental to the surrounding ecosystems (Zhang et al., 2020). Another POP worth mentioning is dichlorodiphenyltrichloroethane (DDT), which has been banned as a pesticide by the European Commission due to its recognized persistence in the human body, but it is still being used in some parts of Africa. DDT is a hydrocarbon that readily binds to lipids in the body, causing some cancers (Adeleye et al., 2019).

Several anthropogenic activities cause excessive accumulation of toxic elements in both land and aquatic environments. These deposits ultimately, skew the natural biogeochemical cycle of these elements, potentially influencing global warming and cooling processes (Galloway et al., 2014). Climate-relevant biogeochemical cycles can be influenced by both rising temperatures and changes in water availability. Climate change and rising temperatures have been shown to interact synergistically with several important elements, exacerbating biodiversity loss, particularly in aquatic ecological systems (Porter et al., 2013). Most civilizations have incorporated wastewater treatment as a strategy between their domestic and industrial activities and the environment and typically include wastewater treatment facilities as part of sanitation, town, and regional planning to ease these issues of pollution.

WWT technology is one of the most thoroughly investigated bioremediation strategies. To reduce the chemical oxygen demand and impurities in wastewater, WWT relies on filtration of macrosolids and aerobic microbial breakdown of complex organic loads. The treatment steps also include chemical treatment, and the final sludge generated is further degraded by AD processes, which generate biogas (methane, CO_2, and hydrogen sulphide) as byproducts, with the end product being useable as biofertilisers. The amount of biogas produced is determined by the organic waste that enters the digester, as well as the microbial consortia attracted by the waste and the ratios of those consortia. Both WWT and AD technologies are not new, but several improvements and additions have been made over the years to both processes. For example, in a recent study by Kumar et al. (2021), the addition of biochar to the AD process significantly increased biogas yields. Similarly, Wambugu et al. (2019) demonstrated that the type of biochar and trace element concentration present in the composition play a key role in determining the effectiveness of the biochar in increasing biogas production from food waste in a series of experiments using different types of biochars. Kanafin et al. (2021) advocate for the combination of anaerobic processes and membrane technology as a promising alternative for municipal WWT but cautions about the challenges associated with the implementation of anaerobic membrane bioreactors. However, Gienau et al. (2018), used membrane filtration on a 2.5MWe agricultural biogas pilot that was run for 7 months to recover nutrients and dischargeable water from anaerobic sludge with significant success (approximately, 70 % solid recovery and 30 % water recovery) while also demonstrating the economic benefits of this process integration to conventional AD technologies.

Following anaerobic digestion, the resulting byproduct "biogas" is purified to yield biomethane by removing trace elements (impurities) and separating biomethane. The most important impurity that is removed is hydrogen sulphide (H_2S) in a desulphurization process. Ryckebosch et al. (2011) reviewed H_2S removal techniques involving the addition of iron oxide pellets or iron chloride. Furthermore, their research investigated the removal of other compounds within the biogas mixture such as siloxanes, hydrocarbons, and ammonia. The final purification step is the separation of biomethane from CO_2. This increases the gas's calorific value. Cryogenic distillation is one method of separation. Yousef et al. (2018) investigated this physical-gaseous separation caused by CO_2 freezing, and they classified CO_2 freezing as a flaw in the system due to pipe blockage. Their research centered on CO_2 liquefaction as a means of optimizing biomethane recovery. Furthermore, Haddad et al. (2021) demonstrated, using mathematical models to determine the levels of frost formation during CO_2 liquefaction.

Almost all human activities, especially industrial pursuits, rely on energy. Water and energy are limited resources, and increasing demand and distribution accelerates their depletion. Population growth exacerbates these shortages (Masdar Institute/IRENA, 2015). Several organizations project a 9.8 billion global population status by 2050 (UN-Water, 2021; Food and Agriculture Organisation, 2018; UN Department of Economic and Social Affairs, 2017). A report by the International Energy Agency and the World Bank (2017), over 1.06 billion people lack access to safe and affordable energy, with half of them living in Sub-Saharan Africa. It is estimated that over 60% of the population in less developed regions rely on this natural system of water replenishment (Mabhaudhi et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) estimates that between 350 and 600 million Africans will face increased water stress by 2055 due to rainfall availability (IPCCW-GII, 2007). Meanwhile, the International Energy Agency (2016) predicts a 30% increase in global energy consumption by 2040. The same agency predicts a 60% increase in total water withdrawals from energy sector activities. This narrative juxtaposes the urgently needed industrialization of Africa. However, these processes will increase water withdrawals, as they are linked to planned economic developments that will lift nearly half of Africa's poor into the middle class.

To sustain this population growth, strategic efforts in developing diverse but sustainable energy resources, as well as evolving water recycling approaches that reduce withdrawals from natural water systems, are required. Furthermore, these strategies must reduce pollution to natural water bodies and drastically reduce indiscriminate discharge of untreated wastewater. Any strategy in this regard necessitates an essential shift in the current paradigm of managing water and energy demand and supply. These two concepts, which are inextricably linked, will have an impact not only on the current situation, but also on future global prospects. The understanding of the current threats to the many limited earth's resources, as well as their continued usefulness in several aspects of human living, has prompted the 2030 global agenda on sustainable development goals (SDGs), which was compiled by the United Nations' 198 affiliate states. Although there are 17 SDGs, at least two of them directly address the water-energy nexus: Goal 6 (ensuring universal access to safe drinking water and sanitation) and Goal 7 (affordable and clean energy) (Mabhaudhi et al., 2021).

Despite the reality that the challenges that humanity faces are complex and frequently intertwined, it is still preferable that rather simplistic approaches to problem solving be used to ensure the ease of replicable solutions. With less than a decade to address the SDGs, it may be advantageous to use the energy potential provided by existing wastewater treatment infrastructure in Sub-Saharan African countries as part of the solution to the water-energy crises. At the moment, the potential and sustainable energy available from wastewater for energy sector development is underutilized. The focus of this study is on Sub-Saharan African countries because of their identified vulnerability and significant population growth over the last two decades. Almost all Sub-Saharan African countries are examined in this review (with the exception of those without data for the period under study). We do, however, draw parallels with advances made in developed countries in terms of water-energy sustainability. It is hoped that the paper will provide potential bespoke solutions for water-energy sustainability based on integrations of ancillary biogas commercial production systems annexed to these countries' existing wastewater treatment infrastructure. Although some countries, such as South Africa, have implemented sludge management at some of the country's wastewater treatment plants (WWTPs) (SABIA, 2018), several African countries are lagging in adoption and implementation, and even in South Africa, there are many WWTPs that could benefit from this inclusion but have not yet integrated the use of anaerobic digestion (AD) as a means of energy harvesting. Particularly when considering the recent energy shortages and rationing experienced in the country. As a result, much more work remains to be done in both the water and energy sectors to leverage this interconnectivity and harness this potential source of renewable and sustainable alternative energy derived from green technologies (Adnan et al., 2019; SABIA, 2018). Most other Sub-Saharan African countries have yet to address this potential resource.

The anaerobic digestion of biomass to produce biogas is considered a carbon-neutral process (Masse et al., 2012; Tetteh et al., 2019) that also lowers greenhouse gases (GHG) emissions, when it collected in a closed system and utilized to effectively produce innocuous gases (Adnan et al., 2019). As a result, this review emphasizes the potential energy that can be harnessed by incorporating AD technology into existing wastewater treatment processes and facilities in Sub-Saharan African countries. Data on global fresh water status was obtained from the World Bank repository and used to demonstrate the energy potential associated with wastewater treatment in Sub-Saharan African countries. Furthermore, while the conversion of clean water resources to wastewater provides the potential for recycling, the eventual sludge build-up associated with at least two stages of most wastewater treatment processes is frequently overlooked. This paper demonstrates that sludge is a potential resource and can best be maximized for electricity generation from its potential biogas outputs. Furthermore, the application and prior AD treatment of sludge provides the added benefit of sanitization and the reduction of pathogenic bacteria such as *Salmonella* sp, *Shigella dysenteriae* and *Vibrio cholera*. associated with untreated sludge. This is because AD processes facilitate microbial successional decline in the closed environment during digestion processes ensuring an almost pathogen-free biofertilizer that can be used for agricultural practices (Kunte et al., 2004).

2. Fresh water status: stress, withdrawal and consumption

Freshwater stress, withdrawal, and consumption are all intertwined phenomena that pose a significant societal challenge. The extraction and transmission of water from natural resources such as rivers, oceans, reservoirs, lakes, and aquifers is the first step in human interactions with the water cycle. The distances, depths, and difficult topography surrounding potable water sources frequently determine the extent of energy requirements for acquisition. For example, the extraction of underground water is a relatively energy-intensive process that may necessitate an estimated 0,0027 kWh of energy to overcome gravity in order to raise 1 m^3 of water. Although energy consumption is dependent on and varies with aquifer depth, output water pressure and flow rate, system efficiency, and local topography, significant energy is required in almost all cases to achieve water collection (Martin and Fischer, 2012; Paul et al., 2016; Kirchem et al., 2019; Kitessa et al., 2020).

Figures 1, 2, 3, and 4 represents how the need for water in various human activities can be broadly classified into domestic, agricultural, and industrial exploits and motivates water withdrawal and consumption. These figures were derived from data collected by the World Bank found on their website (https://data.worldbank.org/indicator/ER.H2O.FWDM.ZS), which serves as a repository for global freshwater withdrawals for various countries (see Table S1). It also has the resulting water stress (The World Bank, 2017). This database covers the years 1965–2017 but for the purpose of this study, we chose to compare two specific years (2007 and 2017) water status data for all Sub-Saharan African countries because data was consistently available with fewer gaps. The information is presented by categorizing countries into four regions (West, East, Central, and South) and comparing these two years. This provides a quick overview of the last ten years of freshwater withdrawals, as well as the corresponding consumption and stress on this limited resource. It should be noted that, according to the World Bank, the level of water stress is calculated as an index of freshwater withdrawal. This calculation yields a fractional value by taking the value of available freshwater resources and dividing it by the amount of freshwater withdrawn by all major sectors, but it also considers environmental water requirements. It should also be noted that the main sectors adhere to the definition provided by the United Nations International Standard Industrial Classification (ISIC) standards, which include agriculture, forestry and fishing, manufacturing, the electricity industry, and services. This metric is also referred to as "water withdrawal intensity." Table 1 compares and averages the distribution of freshwater status across all Sub-Saharan African countries between 2007 and 2017. The observable trend in terms of water stress and withdrawals has remained within the same ranges, though it is notable that freshwater withdrawals are highest for agricultural activities and lowest for industrial exploits, implying most African countries' developing status for industry and manufacturing. In general, the average freshwater stress status for Sub-Saharan African countries is significantly higher than the 6.4 (normal) standard index recommended by the latest FAO/UN joint report

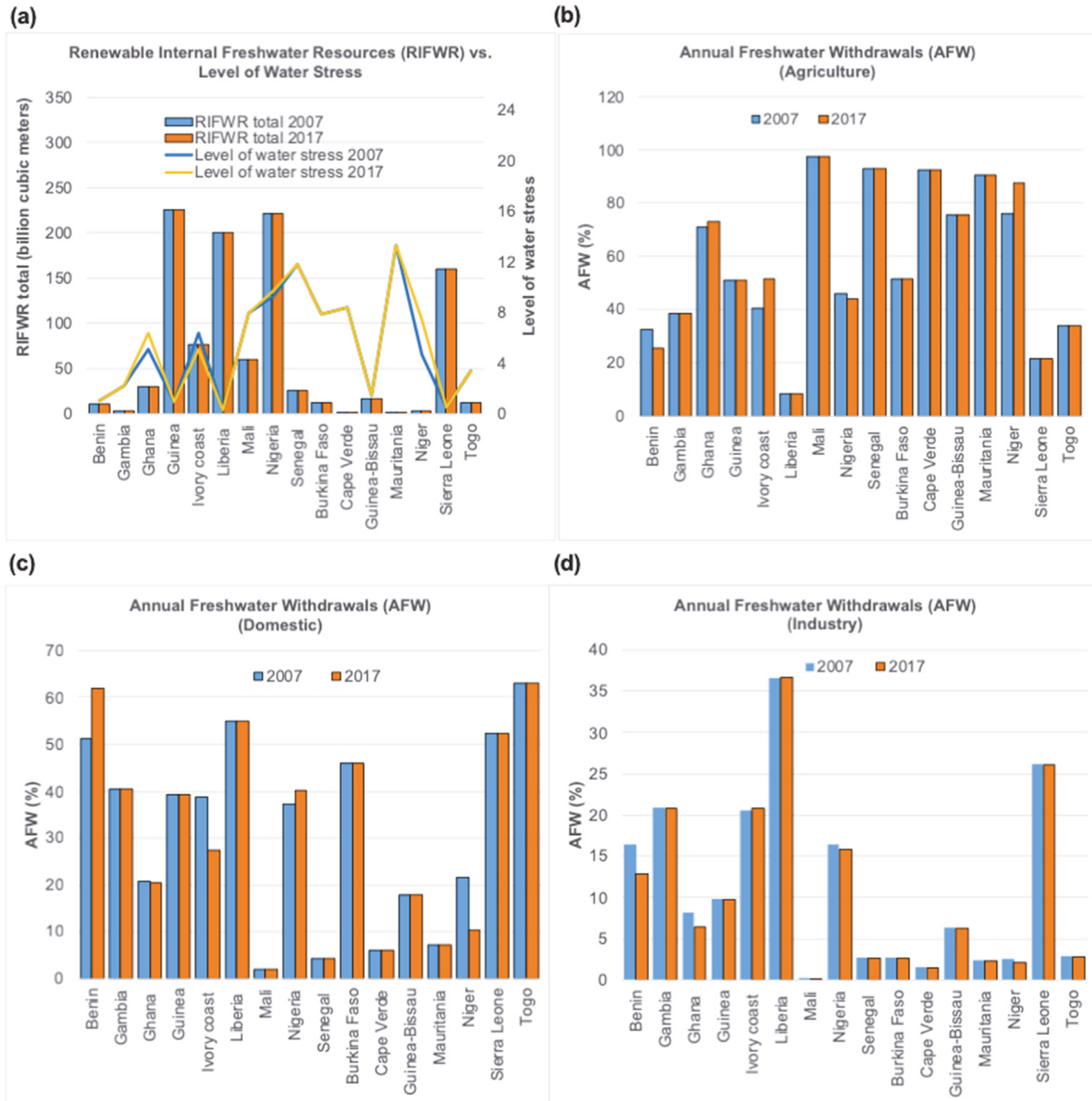

Figure 1. West African Countries Water Status (a) RIFWR versus level of Freshwater Stress (b) AFW (Agriculture) (c) AFW (Domestic) (d) AFW (Industry).

(2021). This confirms the distribution of water challenges observed in the majority of these countries, as well as the need to find solutions to the problems. The routine practice of environmental monitoring and water stress assessment is critical because it encourages consideration of ecosystem health when allocating available resources, thereby preventing the future negative impact of extreme withdrawals.

Freshwater stress is caused by a variety of factors, but the primary push-pull factors are a country's existing renewable internal freshwater resources versus human population density. The interaction of these two factors determines the variations observed across countries and regions. In 2017, Mauritania (13.2), Senegal (11.8), and Nigeria (9.6) had the highest levels of freshwater stress in West Africa, while Liberia (0.26) and Sierra Leone (0.49) had the lowest. In comparison to West Africa, the eastern region has a significantly higher overall level of water stress, with Kenya showing levels as high as 33.2. Surprisingly, Kenya's score increased by ten points in a decade. Kenya far exceeds the FAO/UN (2021) critical index value of 25, which is considered to be extremely detrimental stress levels of freshwater withdrawals. In comparison to both the eastern and western regions of Sub-Saharan Africa, central African countries have relatively low water stress. According to the World Bank's World Development Indicators of 2015, this is most likely due to the region's low population density (The World Bank, 2015). In this region, Chad had the highest freshwater stress of 4.3. Angola is the next country on the list with a 1.9 index. All other countries in the region have indices ranging from 0.1 to 0.5 (see Figures 1, 2, 3, and 4).

Alarmingly, in Southern African countries, Zimbabwe, with a consistent water stress index value of 31.1 over the last decade, and South Africa, which had an extremely high level of water stress of 41.5 in 2007 but has increased significantly to 62 in the last decade, should be cause for concern. These values significantly exceed the considered critical levels of index 25, identifying this region as having the worst freshwater stress crisis in Sub-Saharan Africa. Kenya, in East Africa, has the closest comparison, with levels of 33.2 in 2017. However, it is remarkable that this problem is associated with South Africa, Zimbabwe, and Malawi (17.5), but not with their neighbors, despite the fact that the other countries in this region have freshwater stress levels ranging from 0.5 to less than 1.0. Water stress levels are strongly associated with anthropogenic activities, and it is not surprising that freshwater levels are high in South Africa when we consider the region's economic growth in both industrial and agricultural exploits (see Figure 4).

Agriculture, domestic, and industrial sectors of anthropogenic activities all contribute significantly to freshwater withdrawal (Figures 1, 2, 3, and 4). The West African countries with the highest freshwater withdrawal for agriculture are Mali, Senegal, Cape Verde, and Niger (ranging from 80% to

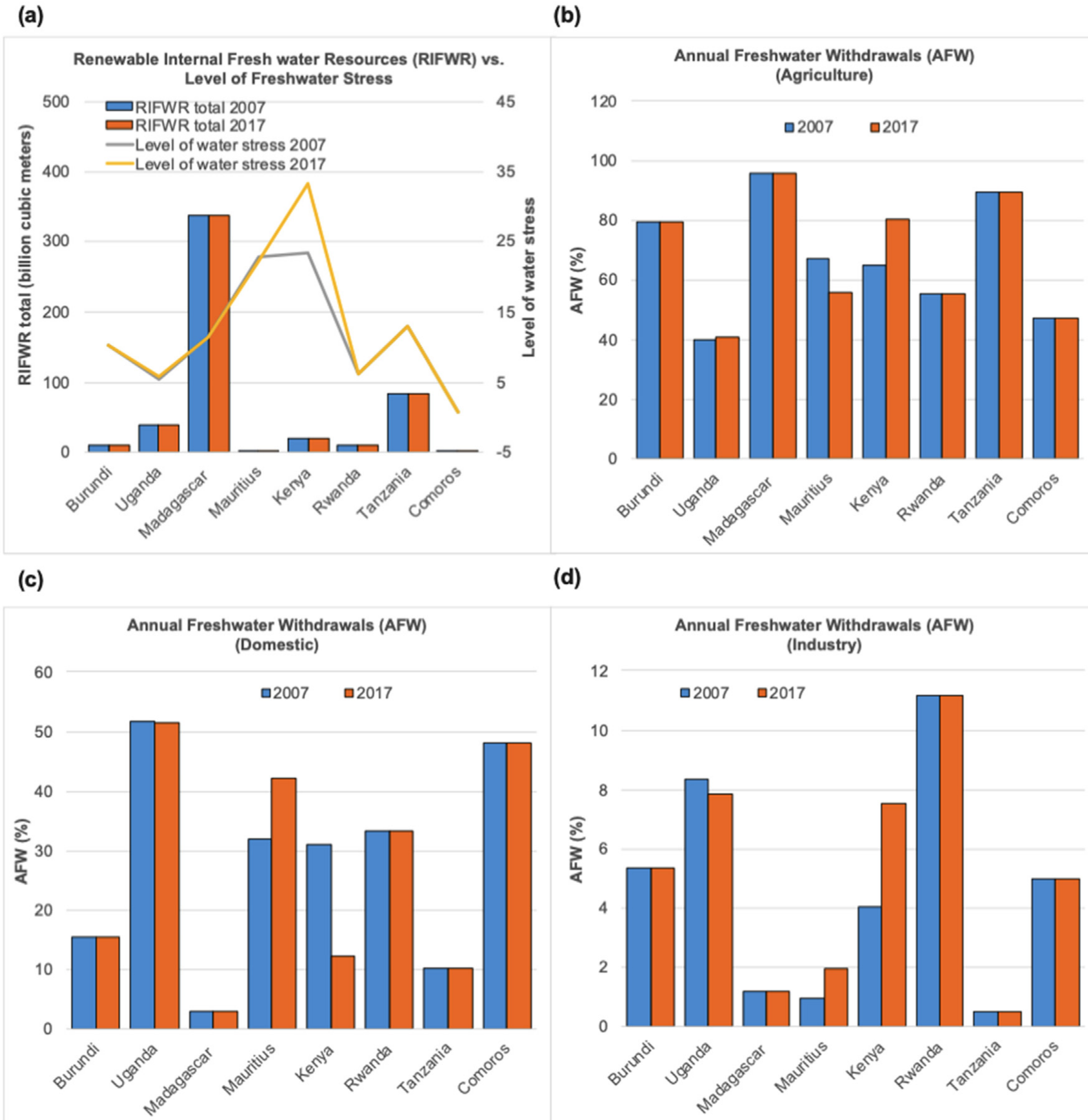

Figure 2. East African Countries Water Status (a) RIFWR versus level of Freshwater Stress (b) AFW (Agriculture) (c) AFW (Domestic) (d) AFW (Industry).

98%), while Liberia has the lowest withdrawal for agricultural purposes (8.4 %). Annual domestic freshwater withdrawal was highest in Togo (63.1 %), Liberia (54.7 %), and Benin, where it appeared to have increased significantly from 51.2 % to 62 % in the last decade, while Mali had the lowest amount (2.06 %). Mali had very little freshwater withdrawal for industrial purposes (0.07 %), whereas Liberia had consistently withdrawn the most water (36 %), followed by Sierra Leone (26.15 %). Although Liberia's renewable internal freshwater resources (RIFWR) are relatively high at 200 billion m^3 and can likely meet the demand for freshwater for industrial activities, Mali has a withdrawal requirement of 97.8 % for agriculture from its RIFWR of 60 billion m^3 (Figure 1).

East African countries had a fairly consistent high range of freshwater withdrawal for agricultural purposes, ranging from 40% (Uganda) to approximately 95.9 % (Madagascar). Annual domestic freshwater withdrawal was observed to be highest in Uganda and the Comoros (51% and 48%, respectively) and lowest in Madagascar (3%). Mauritius increased from 31.9 % to 42.1 %, while Kenya appears to have decreased withdrawal from 31.03 % to 12.27 %. In East Africa, freshwater withdrawal for industrial purposes is relatively low when compared to West African countries, with the highest withdrawal observed in Rwanda over the last decade at 11 % to Liberia (36 %). Although Uganda is second at 7.8 %, and Kenya has increased from 4 % to 7.5 %. This level of freshwater withdrawal for industry in this region is concerning especially with only Madagascar has a significantly good RIFWR (above 300 billion m^3). Other countries in the region have ranges varying from 100 billion m^3 to much lower (Figure 2). As a result, industrial activities must consider alternative water supply sources and reduce freshwater withdrawals from this sector.

The Democratic Republic of the Congo has the highest RIFWR in Central Africa (900 billion m^3), while Chad has the lowest (15 billion m^3). This is also reflected in Chad's large withdrawal (76.42 %) and the region's highest level of freshwater stress (4.3). Domestic freshwater withdrawals in this region range from 12 to 83 %. The Central African Republic (82.89 %) and Equatorial Guinea have the highest domestic withdrawal rates (79.79 %). Chad has the lowest rate at 11.78 %, which is higher than West Africa's Mali (2.06 %) and East Africa's Madagascar (3 %). With 26.17 %, the Republic of Congo had the highest level of freshwater withdrawal for industrial purposes. The Democratic Republic of the Congo came in second with 21.47 %. Both countries in this region are well-known for having extremely high levels of precious metal mining operations. Cameroon has the lowest industrial water withdrawal rate, at 9.6 %.

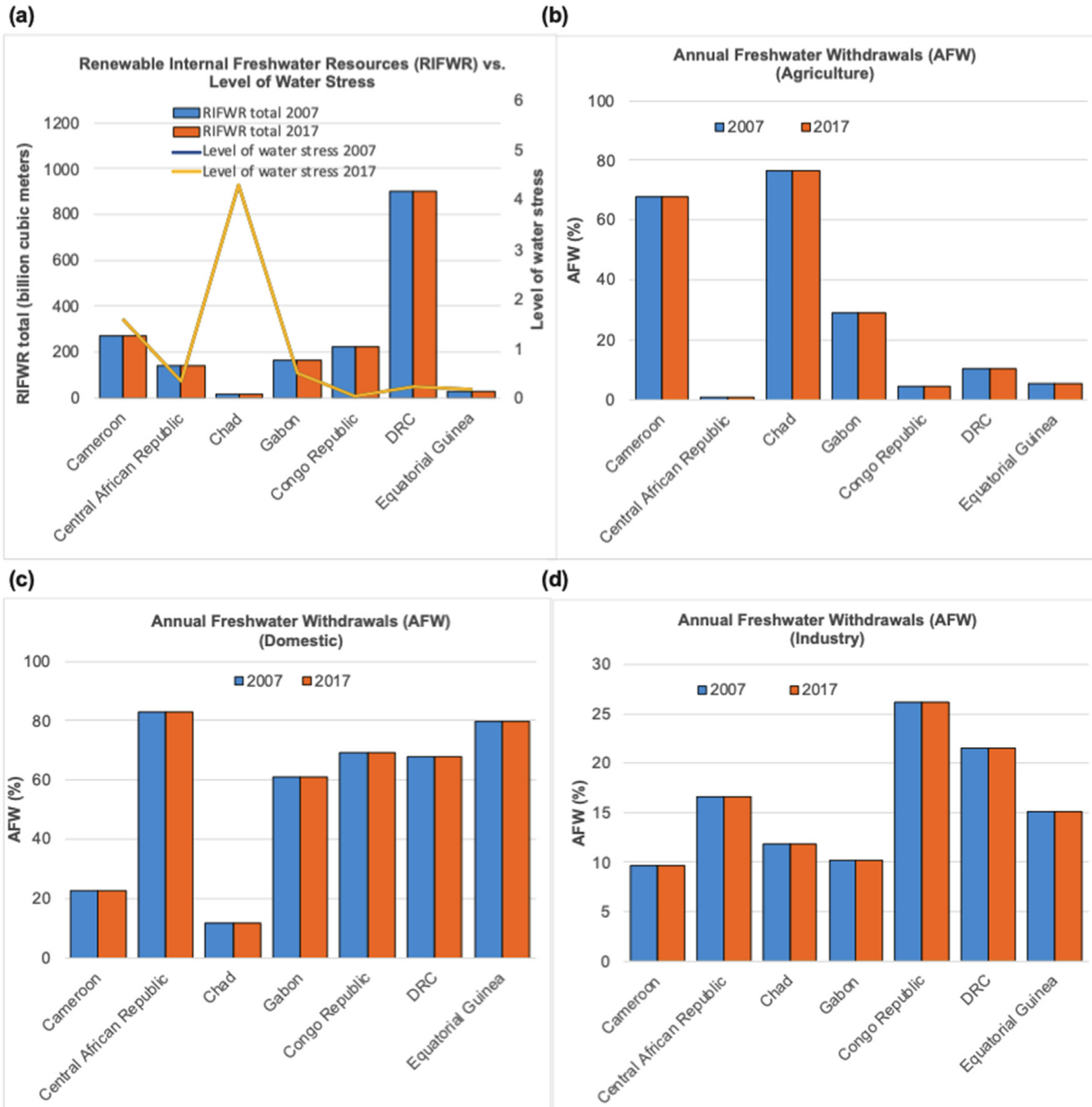

Figure 3. Central African Countries Water Status (a) RIFWR versus level of Freshwater Stress (b) AFW (Agriculture) (c) AFW (Domestic) (d) AFW (Industry).

South Africa has the highest RIFWR in the Southern African region, at 44.8 billion m^3, which is significantly lower than in other regions. Taking into consideration that, in other regions, countries with high RIFWR within their regions have the least effects of freshwater stress as a result of withdrawal. This is not the case in South Africa, which has extremely high levels of freshwater stress (62). A number of countries in the southern region significantly withdraw freshwater for agricultural purposes. Malawi (85.9 %) and Zimbabwe (82.07 %), on the other hand, showed a high level of water withdrawal for agricultural activity. South Africa reduced withdrawal from 62 % to 59 % in 2017, compared to Lesotho's very low withdrawal of 8.67 %. Although, for domestic purposes, Botswana has shown an increase in water withdrawals from 44 % to 52 % as compared to the decrease in South Africa from 28.45 % to 20 %. Other countries in this region reported freshwater withdrawals for domestic use ranging from 10 % to 45 %. Lesotho has the highest industrial water withdrawal rate, at 45.7 %. While Botswana reduced its water withdrawals from 18 to 12 %, South Africa increased from 9.54 % to 21.1 %. Zimbabwe and Mozambique, on the other hand, have reduced fresh water withdrawals for industrial purposes from 6.02 % to 2.4 % and 2.9 %–1.7 %, respectively (Figure 4).

3. Water and energy relationship

Development of electricity generation and its supply in the last 60 years in most Sub-Saharan African countries has included the use of hydropower turbines and the construction of dams. This infrastructure has proven inadequate in meeting energy demands for the growing population. According to Falchetta et al. (2019), over half of the electricity generated in Sub-Saharan Africa is by hydropower (approximately 160 million grid-connected electricity consumers in various countries). Their review further highlight how climate tends to affect power supply reliability. This assertion is further supported by a recent report by IEA (2020) which suggests that climate change is expected to worsen in Africa for the rest of the century, posing a threat to hydropower generation. Climate change will cause severe and regular droughts in parts of Sub-Saharan Africa in the coming decades. We have already begun to witness this, as some of the biggest rivers in Africa have dried out significantly over the last century. The efficiency of hydroelectric dams depends on consistent rainfall, so droughts quickly cripple energy systems that are heavily reliant on hydropower. Additionally, Blimpo and Cosgrove-Davies (2019) report on the effect poor energy supply has had

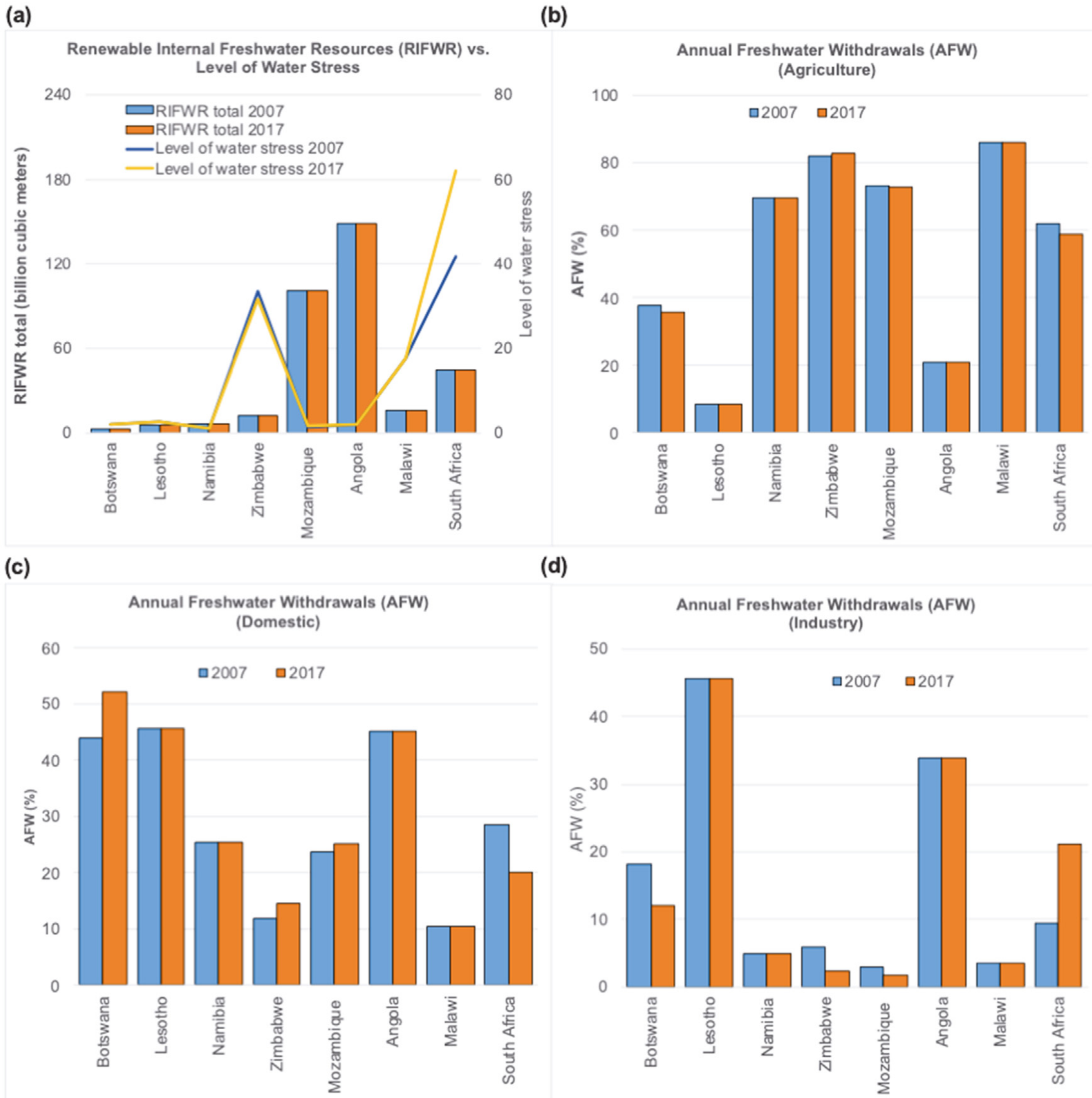

Figure 4. Southern African Countries Water Status (a) RIFWR versus level of Freshwater Stress (b) AFW (Agriculture) (c) AFW (Domestic) (d) AFW (Industry).

on Sub-Saharan Africa's economic growth and ability to adapt. They attribute this failing to two aspects. Firstly, the supply aspects implying that poor maintenance leads to huge technical losses, most state-owned utilities tend to lose money, and the underdevelopment of power exchange, which might significantly reduce electricity costs. Secondly, the demand aspect, where many areas have little uptake and willingness to pay for the electricity usage, and those connected use little as such providing little to no revenue. Increased electricity usage will promote investment in service dependability and access. However, they conclude that climate change is expected to have positive impacts on East Africa's hydropower potential, negative impacts on West and Southern Africa, and no impact on Central Africa.

Despite this, hydropower is needed to mitigate the negative effects of climate change on Africa and can assist Africa in meeting the SDGs, transitioning to clean energy, and adapting to climate change. However, it will only address one aspect of the problem and will not address waste management or the indiscriminate discharge of organic waste into water bodies, which has resulted in the proliferation of water hyacinth and other emergent plant life that are clogging waterways in most Sub-Saharan African countries (UN-Water, 2018). Nonetheless, new and upgraded hydropower projects are being developed across Africa in order to increase energy potential and access to electricity (IHA, 2021). Table 2 depicts some noteworthy old and new hydroelectric power projects.

Table 1. Average freshwater status for Sub-Saharan African Countries (adapted from https://data.worldbank.org/indicator/ER.H2O.FWDM.ZS).

Freshwater Status	Average 2007	Average 2017	Number of Sub-Saharan African countries used to derive averages*
Renewable internal freshwater resources (RIFWR) (BCM)	88.79	87.56	42[ψ] 44[ω]
Level of water stress	7.68	8.58	44[ψ] 44[ω]
Annual freshwater withdrawals, agriculture (%)	53.51	54.11	44[ψ] 45[ω]
Annual freshwater withdrawals, domestic (%)	35.41	33.92	44[ψ] 43[ω]
Annual freshwater withdrawals, industry (%)	11.08	10.82	44[ψ] 45[ω]

[*] Variations in numbers are due to data availability for countries.
[ψ] Representing the number of countries with data available for 2007.
[ω] Representing the number of countries with data available for 2017.

Table 2. An overview of some old and new developments of Hydropower electricity in Africa (adapted from Goosen, 2021; International Water Power & Dam Construction, 2020).

Country and Project	Electricity Generation Capacity	Status
Ethiopia (Millenum/Grand Renaissance Dam)	6 450 MW	Under construction
Ethiopia (Gilgel Gibe Dam)*	≈2 600 MW	Partly completed and some parts operating
Ethiopia (Tekezé Dam)	1 200 MW	Under construction
Egypt (Aswan High Dam)	2 100 MW	Completed and operating
Mozambique (Cahora Bassa Dam)**	2 070 MW	Completed and operating
Democratic Republic of Congo (DRC) (Inga Dams)	1 775 MW	Completed and operating with expected upgrades and expansions to increase capacity to 70 GW
Zimbabwe and Zambia (Kariba Dam)	1 626 MW	Completed and operating with expected upgrades and expansions.
Sudan (Merowe Dam)	1 250 MW	Completed and operating
Ghana (Akosombo Dam)***	1 020 MW	Completed and operating
Nigeria (Kainji Dam)	760 MW	Completed and operating at a lower capacity (original capacity is 960 MW)
Sierra Leone (Bumbuna Hydro II)	143 MW	Construction to commence in 2021
Equatorial Guinea (Sendje Hydroelectric plant)	200 MW	Project yet to commence but has financing
Madagascar (Sahofika Hydropower project)	205 MW	Under construction
Kenya (Kaptis hydroelectric power plant)	15 MW	Project yet to commence but has financing
Kenya (KenGen Hydro Dams Project)	≈826 MW.	Completed and operating
Namibia (Neckartal Dam)	3 MW	Under construction
Malawi (Ruo-Ndiza hydroelectric power station)	8.2 MW	Completed and commissioned for operation in 2020
Lesotho (Polihali Dam and Lesotho Highlands Water Project (LHWP) Phase II)	≈1 GW	Partly completed and some parts operating
Burundi (Dama and Siguvyaye hydropower projects)	7.5 MW Dama 12 MW Siguvyaye	Under construction

* Several dams combined in cascades of Gibe I, II, III, IV and V power stations, but will provide electricity to Kenya, Sudan and Djibouti.
** A portion of the electricity generated is exported to parts of South Africa.
*** Provides electricity to parts of Ghana, Togo and Benin.

Over the last three decades, only a few countries have pursued hydropower diversification, while others' expansion plans will exacerbate their reliance on waterbodies as energy sources. Whereas, other green energy generation solutions, such as biogas production from readily available organics in domestic and agricultural wastes, can provide alternative energy sources. Furthermore, the numerous applications of biogas, including heat, make it worthwhile to pursue. Blimpo and Cosgrove-Davies (2019) emphasized this in their suggestion that hydropower and variable renewables can be planned and managed synergistically to increase resilience and meet these countries' Paris Agreement pledges.

The examination and comparison of overall water usage in relation to energy production versus agricultural and domestic applications are also relevant to this review. This is because several processes in energy production degrade water quality to the point where effluents are frequently impossible to recycle or are completely lost to the process and consumption. However, in both domestic and agricultural processes, the organic content of the wastewater is so high that it should be viewed as a valuable feedstock for energy production. Furthermore, water appears to be required at all stages of energy production. Thermal electrical generation, nuclear power, fracking, hydropower, petroleum refining processes, natural gas industries, and gas-to-liquid technologies all require large amounts of non-potable and potable water supplies (ADNOC, 2018; IEA, 2020; Siddiqi and Anadon, 2011). The latter requirement is used to protect equipment from damage caused by salt deposits on mechanical parts when using salt water or water containing high concentrations of elements. Nonetheless, the use of potable water for these processes significantly contributes to freshwater withdrawal. Water needs, on the other hand, can vary depending on the energy process and technology (Kirchem et al., 2019; Rao et al., 2017). According to reports, the energy sector consumes 64% of the water used in the industrial production of primary energy (IEA & The World Bank, 2017). Primary energy sources such as petroleum, coal, shale gas, and uranium all necessitate a significant investment in water for product extraction, processing, and transportation (Kirchem et al., 2019). Water-consuming processes in these industries include those used as a coolant for chemical processes, as a feedstock for steam production in various chemical processes, and as a hydrogen reservoir (Perera and Zhong, 2017). Water for energy is quantified by measuring the amount of water consumed directly or indirectly per unit of electricity produced (w3/GWh) (Yoon, 2018). Although cooling water does not have to be of the highest quality, water used in these processes must be demineralized in order to reduce salt content, which increases operational costs. Nonetheless, the water used in these industries competes directly with other freshwater applications, and the wastewater generated requires remediation activities before re-use or discharge to natural waterbodies (Sparks et al., 2014). Aside from the energy sector, mining operations make extensive use of water to reduce the risk of fire, as a coolant for cutting equipment during processes, and to control dust buildup. Furthermore, water is used in the ore extraction and separation processes for mixtures and slurry transport. Some of the processes can incorporate the use of sea water rather than freshwater, but this is not always considered, possibly due to proximity and the additional cost of transporting the latter the long distance to where the mines are located. As a result, in most cases, freshwater from a nearby source is used. The effluent produced frequently runs off and is discharged directly into freshwater bodies of water. Graywater derived from domestic use can be used in agriculture as a replacement for cleaning and in some irrigation applications. However, the process of natural water cycling and movement frequently implies that polluted run-offs containing significantly high levels of organic and inorganic compounds, such as nitrates and phosphate that eventually contribute to the pollution of nearby freshwater sources.

In summary, only few processes produce wastewater that can undergo valorization towards energy production. Agriculture and domestic wastewater have these qualities and can therefore be employed in this beneficiation process of biogas production.

4. Electricity usage and shortage crisis

The most useable form of energy for anthropogenic activities is electricity, and as such, it has remained an essential commodity for economic development since its invention. Electricity is considered a key factor in achieving sustainable development and economic prosperity (Chirambo, 2018; Olanrewaju et al., 2019). Electricity is a necessity for any nation seeking industrial and economic growth. Consistent energy supply is required for industrial equipment, domestic (lighting and heating), transportation, and several other endeavours (Ibrahim et al., 2021). Ultimately, industrial growth attracts socio-economic growth, which many nations strive to achieve (Sambo et al., 2010; Kraus and Kraus, 2021; Kihombo et al., 2021).

Globally, electricity supply and availability fluctuate due to economic disparities. Around 759 million people lack reliable access to electricity, while another billion receive substandard or prosaic quality of service (Szabó et al., 2013; Ritchie and Roser, 2020). This underserved population can be predominantly found in Sub-Saharan Africa and South Asia (Nerini et al., 2016). Contrast this with the developed world, which has reached nearly 100% electrification in the last decade (Szabó et al., 2013). In 2016, only 42.8% of Africans were electrified, far below the average for developing countries. To clarify, 770 million globally lack electricity, with 75% of this population residing in rural areas (IEA, 2019). Sub-Saharan Africa is estimated to account for 61% and Asia for 35% (REN21, 2019).

Almost 790 million people resort to solid biomass for heating and cooking (Eskom, 2017). Presently, only six countries have household electricity coverage of at least 75%, with Mauritius and Seychelles being the only two with universal coverage (Blimpo and Cosgrove-Davies, 2019). Conversely, nearly a third of the Sub-Saharan African countries have household electricity access rates of at least 30% (Tagliapietra, 2018).

National electrification processes are difficult and time-consuming, with some studies estimating that it takes an average of 25 years to increase electrification levels from 20 to 80 %, or 2.4 % per year (Castellano et al., 2015). Although some countries, such as Vietnam, completed the task in nine years, it took Brazil more than 40 years to complete the electrification of all of its regions. However, as Blimpo & Cosgrove-Davies (2019) states electrification is occurring at a rate far below the global average in Sub-Saharan Africa. The Sub-Saharan region has the world's lowest capacity for electricity generation and suffers from the most severe forms of energy poverty (Prasad, 2011; Hafner et al., 2018).

Nigeria is one of several African countries that continues to suffer from a severe lack of adequate electricity (see Table 2). Especially given that it is Africa's most populous country, with over 205 million people. Nigeria has had problems with electricity generation, transmission, and distribution for over 60 years (Uzorh and Innocent, 2014). According to the most recent Global Energy Outlook in 2021, approximately 57.3 % of Nigeria's population had access to electricity (IEA, 2021). For electricity generation, the country relies on hydropower plants in Kainji, Jebba, and Shiroro in central Nigeria (Ibrahim et al., 2021), as well as other sources of electricity such as fuelwood/biomass consumption and petrol/diesel-powered generators (Omoruyi and Idiata, 2015; Lawal et al., 2020). Nigeria is currently the world's largest purchaser of standby electricity generating plants (Braimoh and Okedeyi, 2010; Lawal et al., 2020). This is associated with noise and air pollution. It is difficult to eliminate this electrification option, which is unlikely to change in the absence of laws and policies that support energy privatization and commercialization, that could improve access as a result of competition. Cameroon's situation may be considered worse, with only 20% of both rural and urban populations having access to direct electricity, with rural populations accounting for 4–6% (Vintila et al., 2019; Nemzoue et al., 2020; Guefano et al., 2021). According to Kidmo et al. (2021) Cameroon currently gets the majority of its energy from biomass. This is due to her potential in Sub-Saharan Africa as the second largest in terms of biomass possession in the form of forestry. Forest in this country, covers nearly three-quarters of the country (21 million hectares) (Wandji, 2013). However, with the knowledge we now have about the effects of deforestation on global warming, this rapid degradation of the environment for energy generation is not sustainable and should be discouraged.

South Africa is considered to be ahead of most Sub-Saharan African countries in terms of economic and infrastructure development. South Africa's total installed electrical capacity was 48 GW in 2018 (Eskom, 2018). However, the country hopes to transition to sustainable energy in the future in order to reduce greenhouse gas emissions associated with its current form of electricity generation and other industrial processes, but this progression has remained rather slow. Although, it maintains a national electrification rate of nearly 90%, which places it ahead of most Sub-Saharan countries (Eskom, 2021). Nonetheless, the country has been experiencing an unabated power shortage since the early 2000s (Pretorius et al., 2015). As a result of the inability to maintain demand for at least 39, 000 MW per day, there has been incessant blackouts or power cuts (Renke and Reinhard, 2020). The term "load-shedding" was coined to reflect growing concern about the current and future reliability of South Africa's energy supply. It has also become a routine event with constant power outages experienced daily in various parts of the country. Vermeulen (2020) emphasizes the impact of load-shedding on economic development, estimating that economic growth has been reduced by 1.1 % as a consequence. Despite these challenges, the country's average electricity consumption was approximately 3,500 kWh in 2020, with a population of approximately 59.4 million people. This consumption was approximately ten times than that of the rest of Sub-Saharan Africa (Department of Energy (DOE), 2019). Eskom, the national power utility company, has provided projections on the state of electricity supply, indicating that if power stations do not improve their grid and supply over the next five years, there will be an energy deficit of 4000–6000 MW. These projections are based on estimates of the life-cycle of existing coal-fired power plants, which would reach their end-of-life even with maintenance (Wirth, 2020).

Overall, Sub-Saharan Africa's electricity supply crisis is the result of the energy sector's over-reliance on fossil fuels (Ebhota, 2019). Prospects for renewable alternative energy sources, as well as the potentially significant contributions they could make, are currently being overlooked. Furthermore, the disparity between rural and urban electrification persists, implying that economic growth will continue to be incongruous and will drive transmigration within different countries' borders, exacerbating the imbalance. The African continent is characterized by high population growth and rising income levels. This growing population is increasingly urbanizing and will constantly require electricity and lighting. Over the last decade, significant numbers of people have migrated to cities, and this trend shows no signs of abating. Based on projections from a report by African Development Bank (2014) it is estimated that by 2040, at least 580 million people will have been added to the majority of urbanized areas. This rate of population growth and skewed density have a negative impact on resource availability and is not aligned with current infrastructure development. Nevertheless, even in areas where there has been a compelled increase to meet demand, such as agricultural production and an increase in the number of vehicles for transportation of people and goods, there has also been a necessary increase in energy demands to support these developments (Ibrahim et al., 2021). Energy scarcity eventually leads to supply shortages and poor infrastructure, which have a knock-on effect on their economies (Goldberg, 2016; Chakamera and Alagidede, 2018; Ateba and Prinsloo, 2019).

5. Effects of electricity shortages to economic development

Most countries' socioeconomic growth is heavily reliant on foreign investors. These investors frequently assess a country's political, environmental, and socioeconomic landscapes before investing. Africa, in general, benefits from its large workforce and bias towards the age demographics, which are primarily between the age group of 18 and 40.

These age groups have the potential for accelerated economic growth, if the workforce is well-managed. Furthermore, most African countries have a diverse range of resources and raw materials for industrial use. However, the lack of a well-managed water-energy nexus has long been a deterrent to growth. Furthermore, the significance of electrification to economic development cannot be overemphasized. In terms of reliability, Africa's energy sector has a poor track record, with the continent experiencing 56 days of power outages on average per year (United Nations Environment Program (UNEP), 2013). Nigeria (4,600 h), Niger (1,400 h), the Democratic Republic of the Congo (830 h), Cameroon (790 h), and Ghana (790 h) had the longest power outages in 2018 (Alves, 2021). These factors have reduced foreign investment appetite in some Sub-Saharan African countries because the infrastructure development required to support certain businesses and investments is daunting to undertake and serves as a barrier to entry. Even existing businesses are closing down, resulting in significant job losses as a result of the costs incurred due to downtime experienced during these regular power outages that disrupt supply chains. Changes to entire supply chains of goods and services can cause a country's market to become volatile, making investors wary of putting their trust and resources in such countries. As a result, several multinational corporations have withdrawn from some African countries. In addition, households suffer from the consequences of insufficient electricity supply. Since electricity is the fundamental need for households, communities are unable to carry out daily tasks. Consequently, consumers have lost trust in the service utilities tasked with providing safe and dependable energy. This trend of a lack of access to electricity has become one of Sub-Saharan Africa's major impediments to economic growth and small business development (Panos et al., 2015).

Most businesses have resorted to using backup generators to provide electricity to support the structure of their business, with the additional costs of fuel and maintenance driving up the final cost of goods and services. Traditionally, these backup generators were installed in large buildings, hospitals, shopping malls, factories, and homes to supplement power supply during outages and support existing electrical generation capacity. However more often than not, it has become the main power supply. Sub-Saharan Africa has the highest share of electricity output from generators in the world, accounting for 9% of annual electricity consumption, compared to 2% in second-place South Asia. According to recent estimates, Sub-Saharan Africa has 6.5 million generators spread across the region, with Nigeria having the majority (approximately 3 million generators). Furthermore, West Africa has the highest share of power generated by backup generators, accounting for approximately 40% of yearly usage, which is four times the share of power generated by backup generators on the opposite side of East Africa (Gandi, 2019).

Due to the obvious reliance on fuel-based generators, the introduction of domestic biogas digesters with the prospect of lowering the cost of purchasing fossil-derived fuels had initially gained significant acceptance. However, sustainability in terms of management and general housekeeping required for anaerobic digestion technology quickly dampened the appetite for domestic use. Table 3 summarizes the difficulties encountered in the development of biogas technology as reported by several researchers in current literature, over the last decade. Most authors explained that people generally struggled with the maintenance of domestic digesters for cooking and heating needs and were unable to process biogas applications for electrification or maintain it, long-term. Anaerobic digestion technology is relatively new in Africa, as such, it

Table 3. Barriers to biogas implementation in Africa.

Category	Barrier	Reference
Technical	Inadequate feedstock supply	Hasan et al., (2020)
	Lack of education on biogas technology at different educational spheres.	Mukumba et al. (2016)
	Lack of information on economic feasibility	Tucho et al., (2016)
	Lack of land	Hasan et al., (2020)
	Absence of putative technology and grid infrastructure	Kemausuor and Ackom (2016)
	No clear energy policy and support	Kemausuor et al. (2018)
	Insufficient designs and construction of digesters	Mohammed et al., (2017)
	Lack of sufficient knowledge on biogas as dual 'fuel production and waste management technology'.	Muvhiiwa et al. (2017)
Economic/Financial	Large initial investment costs	Muvhiiwa et al. (2017)
	High maintenance and operational costs	Roopnarain and Adeleke (2017); Nevzorova and Kutcherov (2019)
	Reluctance from financial institutions due to high risk and low recovery	Mittal et al. (2018)
	Lack of support from government to project developers	Sakah et al., (2017)
	High central bank rates = high lending rates and restricts long-term financing of projects	Schmidt and Dabur (2014)
	Competition with other investments	Hasan et al., (2020)
Government/Regulatory	Lack of financial policy	Hasan et al., (2020); Uhunamure et al. (2020).
	Lack of interest from government	Roopnarain and Adeleke (2017); Sakah et al., (2017)
	Lack of coherent and robust biogas strategy/policy	Hasan et al., (2020)
	Uncoordinated link-up between important stakeholders (central government agencies, research institutions and business firms).	Yousuf et al., (2016)
	Legislation does not accommodate for projects, too many documents requirements (e.g. licences, agreements) from various regulatory institutions which add to costs and opens an avenue for corruption	Pueyo (2018)
Global Market/Awareness	Volatile energy market	Kemausuor et al. (2018)
	Lack of demand from primary-end-user	
	Competition with fossil fuels, opening avenues for sabotage	Kemausuor et al. (2018)
	Lack of private investment	Hasan et al., (2020)
	Lack of awareness on policies, technologies and processes	Nevzorova and Kutcherov (2019)
	Unreliable service delivery and utilities as too many risks associated with signing Power Purchase Agreements (PPAs) with them.	Pueyo (2018); Uhunamure et al. (2020).

cannot be overlooked that it necessitates a skilled understanding of optimal conditions and precise control of biotic factors essential for the growth of the rather fastidious methanogenic microorganisms and the further requirements of extreme anoxic conditions for proliferation and biogas production. This knowledge base is a purview of trained microbiologists, biotechnologists and chemical engineers. Consequently, domestic and single-unit applications may not be optimal for achieving maximum results in the progressive adoption of this type of green technology. However, for long-term sustainability, industrial upscale may be best for biogas production, where adequate monitoring of all contingencies associated with its operations are factored into process management. Examples of such upscale biogas production where biogas production may benefit the African context will include its incorporation as part of a circular economy strategy into commercial farms with an adequate and consistent supply of organic waste to sustain production. Subsequently, its inclusion and installation and maintenance costs are offset by the benefits it provides in terms of energy independence for ancillary food processing and general farming operations, the environmental consideration that it provides, as well as the waste management strategy it offers to farmers. Food manufacturing companies, hospitals, restaurants, and wastewater treatment plants benefit from this same approach as well. In such operations where biogas technology is integrated for the multiple benefits that it provides, skilled personnel are necessarily included to manage the operations and optimize biogas yield and to improve profitability. Furthermore, in developed countries where biogas technologies have been successful, household and consumer interactions with the technology is primarily through finished products such as heat, methane gas, and electricity and not with its daily management. This assertion is supported by the recent research and survey conducted by Uhunamure et al. (2020), which demonstrates low awareness, perception, and utilization of biogas technologies is still an issue after over 10 years of domestic use and implementation, despite the investment efforts made in its development at the community level in South Africa. Therefore, this study proposes a strategy shift in which investment efforts should be focused on developing large-scale biogas production and delivering end-products to individuals rather than the

Table 4. Some examples of successful and active centralized biogas commercial plants in Europe, Africa and Asia.

Country (city)	Year	Feedstock	Capacity (MWh)/year	Application	Estimated investment (million USD)	Investment Model	References
Finland (Helsinki)	2013	Wood residue	140	Electricity generation & district heating	52	Financial aid from Ministry of Employment and the Economy ($13M) and Nordic Investment Group ($23M, 4M)	France-Presse, 2013
Finland (Lahti)	2015	Organic waste	50 GWh	Gas networks for transport, fertilizers and plant growth substrates	19.5	Joint venture partnership (Labio + Gasum)	WWF, 2015
Poland (Lazniki)	2019	Beat pulp & Maize silage	8 000	Electricity power plants	6.1	Joint venture (Wroclaw university of Science and Technology with + EU's regional operational program- $3.1M)	Grants Map (EU), 2020
Finland (Lohja)	2021	Biowaste from domestic, industrial and retail activities. Slugde from WWTP.	40 GWh	Liquefied biogas injected into gas network (LBG) and organic fertilizer	9	Government funding (Ministry of Economic Affairs and Employment)	Bailey, 2021
Serbia	2016	Agricultural biomass residue	1.2	Electricity and heating	6.1	Joint venture (PEPO energy + MET Group & Arher Teh)	Ellaktor Group Construction, 2019
Krabi (Thailand)	2016	Palm oil mill effluent	12 300	Electricity (national grid & supply plant) + methane capturing	na	Private (loan supplied by Caterpillars Inc. Investment)	Coonan, 2016
Kenya (Naivasha)	2016	Agricultural residue (Near farms)	2	Cultivate vegetables, flowers, power for rural homes and fertilizer	7.5	Private (Vegpro Group)	Bungane, 2017
South Africa (Gauteng)	2015	Biomass waste (cattle manure & organic municipal waste)	4.4	Supply BMW factory with electricity (30–35%) and excess integrated into Eskom supply	11	Private equity + Loans (Bio2wattCape Diary + Norfund, Bosch Holdings, Bertha Foundation)	Eskom Group, 2017
Dubai (Warsan)	2019	Domestic sewage	45 000	Electricity (Alternative source of energy for the plant)	89	Public-private partnership (Dubai municipality & Veolia)	Meladi, 2019
Bulgaria (Sofia)	2021	Domestic sewage	2.4	Electricity (powering operations of plant)	4	Sofiyska voda (Veolia's subsidiary)	
Sebia (Krusevac)	2019	Domestic sewage	3.8	Electrcity is used to conduct optimal operations for the facility and heating.	29.4	Consortium-AKTOR (99,96%) and Waterleau Group NV (0,04%)	MET Group, 2021
U.S.A (Gresham, Oregon)	2015	Domestic sewage	6 000	Electricity for half of facilities energy use and heat	na	na	Hayward, 2018
U.S.A (Clackama's County, Oregon)	2021	Domestic sewage	4 324	Electrification and excess heat captured and used to heat digesters as well as space heating.	na	Energy Trust & Clackamas Water Environment Services	Clackamas County, 2020; Loggan, 2021

na: not available.

current investments, finances, and subsidies used for single units and household biogas production. This is based on the minimal traction that community based biogas technology dissemination has made in the last decade and the shared sentiments of discouraging outlooks that researchers have made as shown in Table 3. It is our conviction that it will continue to be a difficult task to educate unskilled individuals on the finer details of sustaining the consortia of microorganisms required for biogas production, as well as other factors required for the chemical purification of biogas for use in different applications. Thus, the focus should rather be the support by government and private companies of large scale production and distribution of finished products of anaerobic digestion technology including biogas to the people.

The commercialization of biogas processes presents its own set of challenges, including the significant capital investment required for its inception and establishment. However, most developed countries that have adopted this strategy have conducted several techno-economic feasibility studies detailing the progress, drawbacks and necessary adaptations towards the present routine application of biogas as supplement to other forms of sustainable energy. Furthermore, there is a wealth of literature that discusses the advantages of its implementation in waste management as well as the environmental benefits it brings to the achievement of net zero carbon emissions (Lawson et al., 2021; Glivin et al., 2021; Ferella et al., 2019; Di Perta et al., 2019; He et al., 2018; Naami, 2017; García-Gutiérrez et al., 2016). Some of these papers even

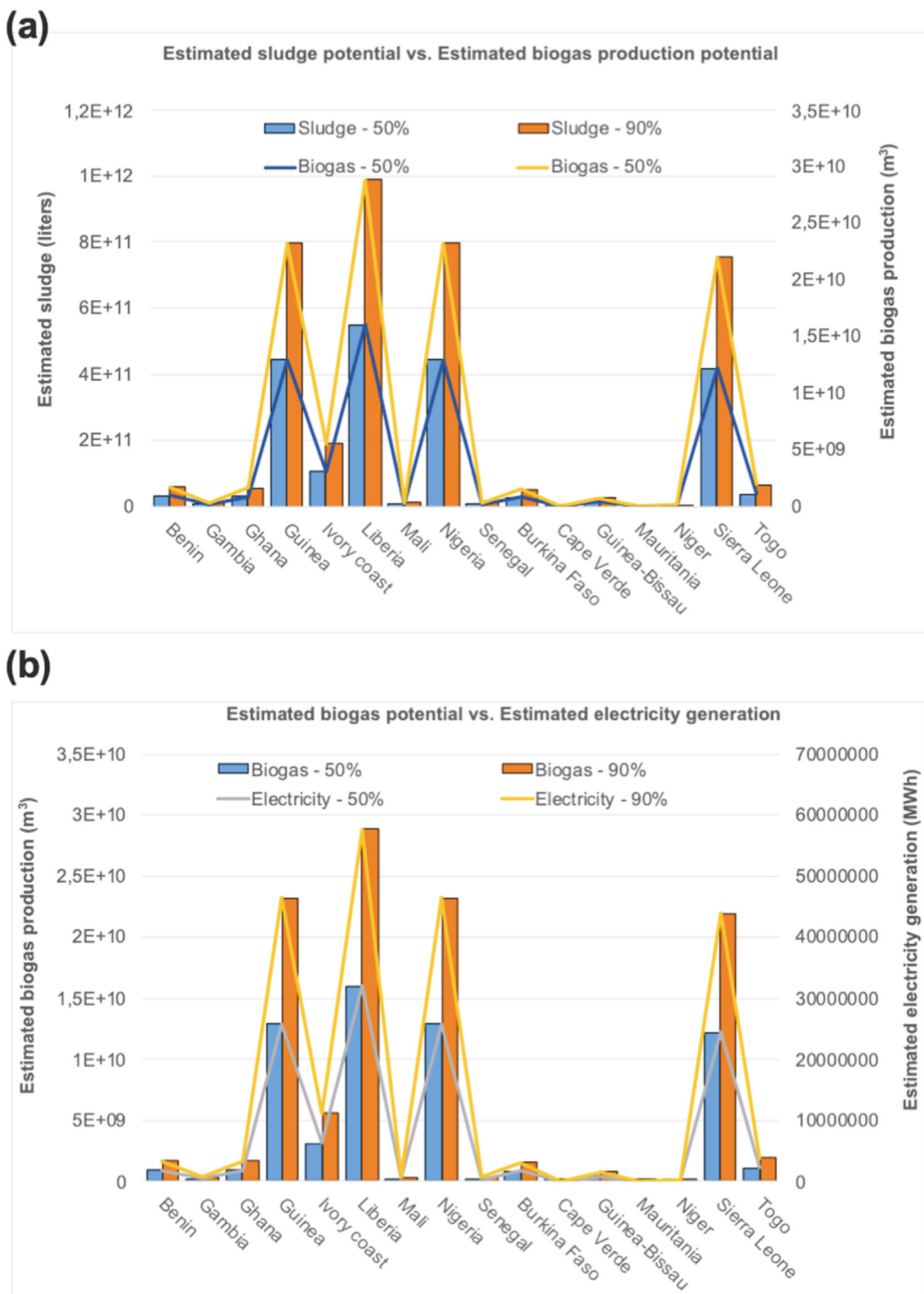

Figure 5. a–b West African Countries potential biogas and electricity generation from estimates of 50% and 90% wastewater derived from domestic freshwater withdrawals from World Bank data.

discuss the profitability of inclusive enterprises and the management. This implies that such information is not scarce for Sub-Saharan African countries planning to implement these technology adaptations for WWTPs. The availability of information reduces the investments on techno-economic feasibility studies as there are aspects that can readily be adapted to most situations.

However, the critical barriers to commercial biogas production in Africa can be summarized in terms of technical, economic, financial, government/regulatory barriers, market, and awareness, as shown in Table 3. Pertinently, the nature of management of such an enterprise is key to its success. Ateba et al. (2019) examined the negative impact of public sector management of energy supply on small and medium-sized businesses, arguing that the public sector's lack of governance and long-term management of business skills in this sector are major factors leading to the failure of electricity delivery. Privatization of electricity supply and distribution does provide some benefits in terms of supply consistency. Profitability is the motivation for private sectors, in this aspect it ensures good management. The implication is that more control measures will be put in place to ensure that the business meets its deliverables to investors and consumers. Hulák et al. (2018) provide insights on the involvement of private companies in the supply of electricity, demonstrating that higher levels of private energy sector involvement result in higher levels of energy efficiency and quality of energy supply. When private companies participate, distribution and revenue collections from energy consumption improve. Furthermore, in public-private partnerships, the private sector is responsible for the upkeep of government-provided infrastructure, ensuring continued productivity and the longevity of the business life cycle. Overall, such joint ventures with minimal government interference are more likely to succeed. Table 4 shows some examples of successful joint ventures in the

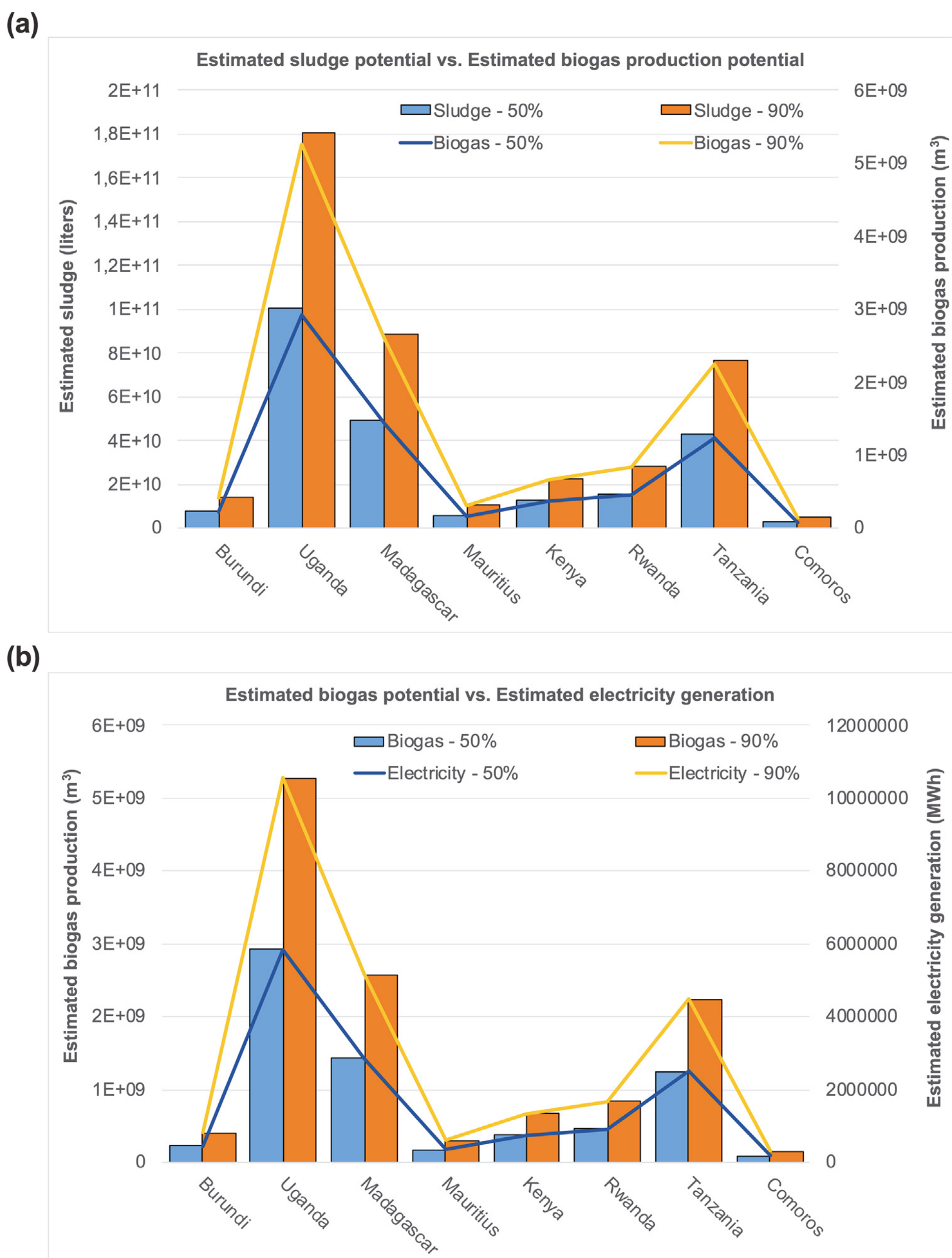

Figure 6. a–b East African Countries potential biogas and electricity generation from estimates of 50% and 90% wastewater derived from domestic freshwater withdrawals from World Bank data.

commercial production of biogas and the generation of electricity. It is worth noting, that most of these biogas plants boast of significantly reducing carbon emissions. For example, with the Warsan, Dubai commercial biogas plant, it is the first to produce green energy in the country and reduce carbon emissions in the region by 31 000 tons per year (Table 4).

6. Wastewater generation and data capturing challenges

In this review paper, we used data from the World Bank's Freshwater Status database (Table S1) to demonstrate how three major anthropogenic activities consistently contribute to freshwater stress in Sub-Saharan Africa (Figures 1, 2, 3, and 4). There is an inevitable implication that wastewater will be generated as a result of these activities. Agriculture, domestic, and industrial activities all contribute to pollution in different ways due to the different pollutant chemical compositions. Most wastewater from domestic and agricultural processes would be high in organic compounds, nitrates, and phosphates, whereas industrial effluents frequently contain toxic elements and vary depending on the industrial process and products. For example, petroleum industry would produce effluents that contain hydrocarbons (Qaderi et al., 2018; Sanchez-Salas et al., 2016); the paint industry will generate wastewater that specifically contains propylene glycol, ethylene glycol and iso-butanol (Krithika and Philip, 2016); brewery effluent will be high in sugars, soluble starch, ethanol and volatile fatty acids (Jaiyeola and Bwapwa, 2016; Simate et al., 2011); tannery effluents will contain

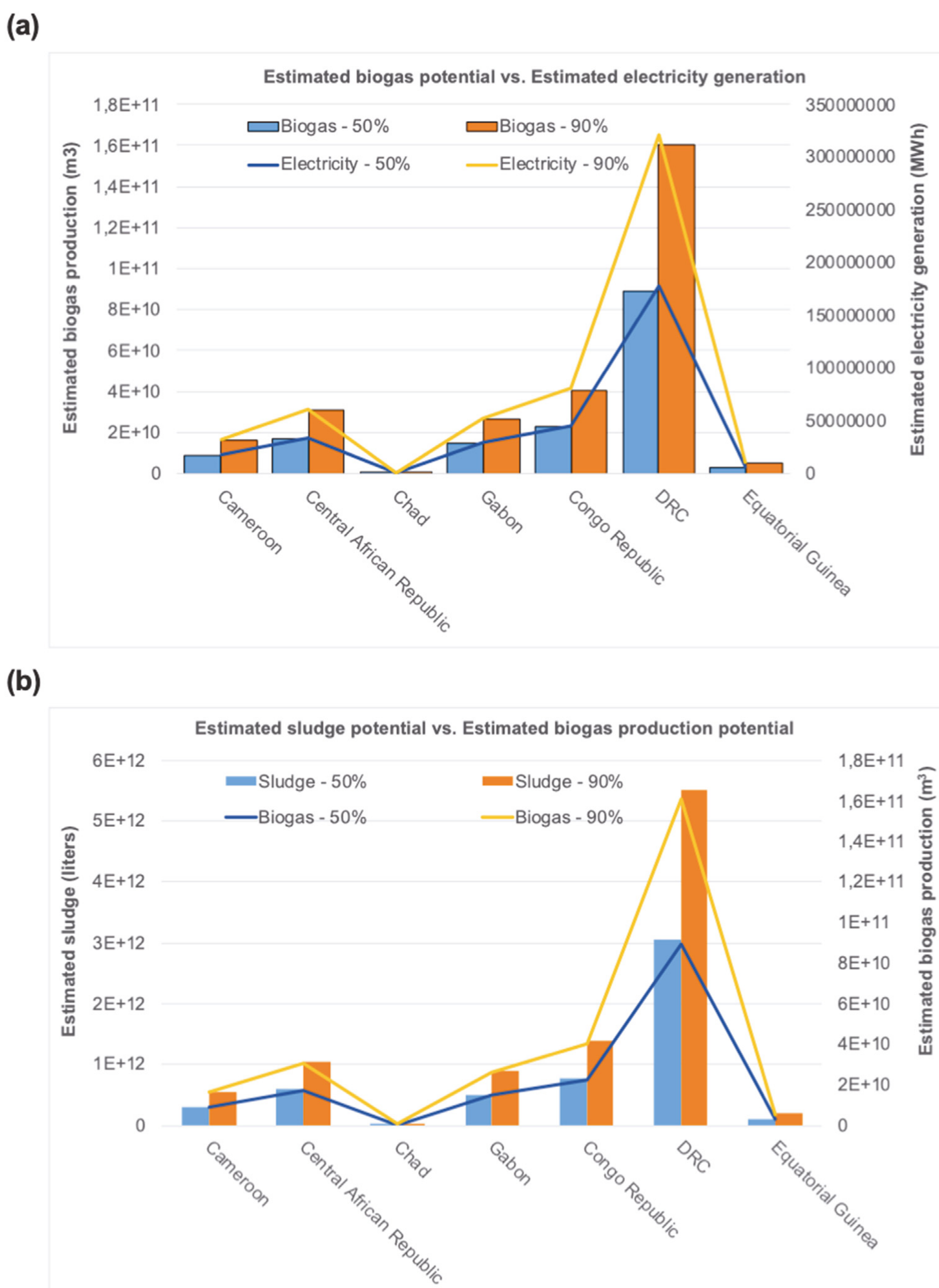

Figure 7. a–b Central African Countries potential biogas and electricity generation from estimates of 50% and 90% wastewater derived from domestic freshwater withdrawals from World Bank data.

considerable amounts of chromium (Oruko et al., 2021) and the Fischer-Tropsch synthesis process for coal conversion to energy typically contain hydrocarbons, fatty acids and alcohols (Malematja et al., 2020).

In general, all of these pollutants are associated with high levels of chemical oxygen demand (COD) in effluents, necessitating treatment to reduce COD levels before subsequent discharge into natural waterbodies. As a result, COD is regarded as one of the most important standard measurements for determining the efficacy of wastewater treatment (Jia et al., 2019; Nayl et al., 2017). Water must be treated in accordance with the various water regulation standards of each country, depending on the end use. In China, for example, the acceptable limits for COD and BOD are 120 mg/L and 30 mg/L, respectively, whereas in Denmark, the COD limit is 75 mg/L and the BOD acceptable limit is 10 mg/L. In South Africa, the acceptable limit for COD is 75 mg/L, and the acceptable limit for BOD is 30–40 mg/L (DEA 2014). The general consensus is that COD must be significantly reduced before discharge, with conscious regard for the aquatic ecological system, because the long-term consequences affect all inhabitants, including humans.

In most Sub-Saharan African countries, an insufficiency of centralized and decentralized wastewater treatment facilities is a major issue. Such facilities are frequently disproportionately distributed and inadequate to accommodate the growing population of people living in particularly dense urban areas. They are frequently not designed to manage concurrent industrial activities or ensure the removal of persistent toxic elements (Wang et al., 2014). This typically results in untreated waste spilling into streets or being discharged indiscriminately into nearby natural waterbodies without any treatment to reduce COD and toxic element concentrations, as well as the likely presence of pathogenic microbial organisms,

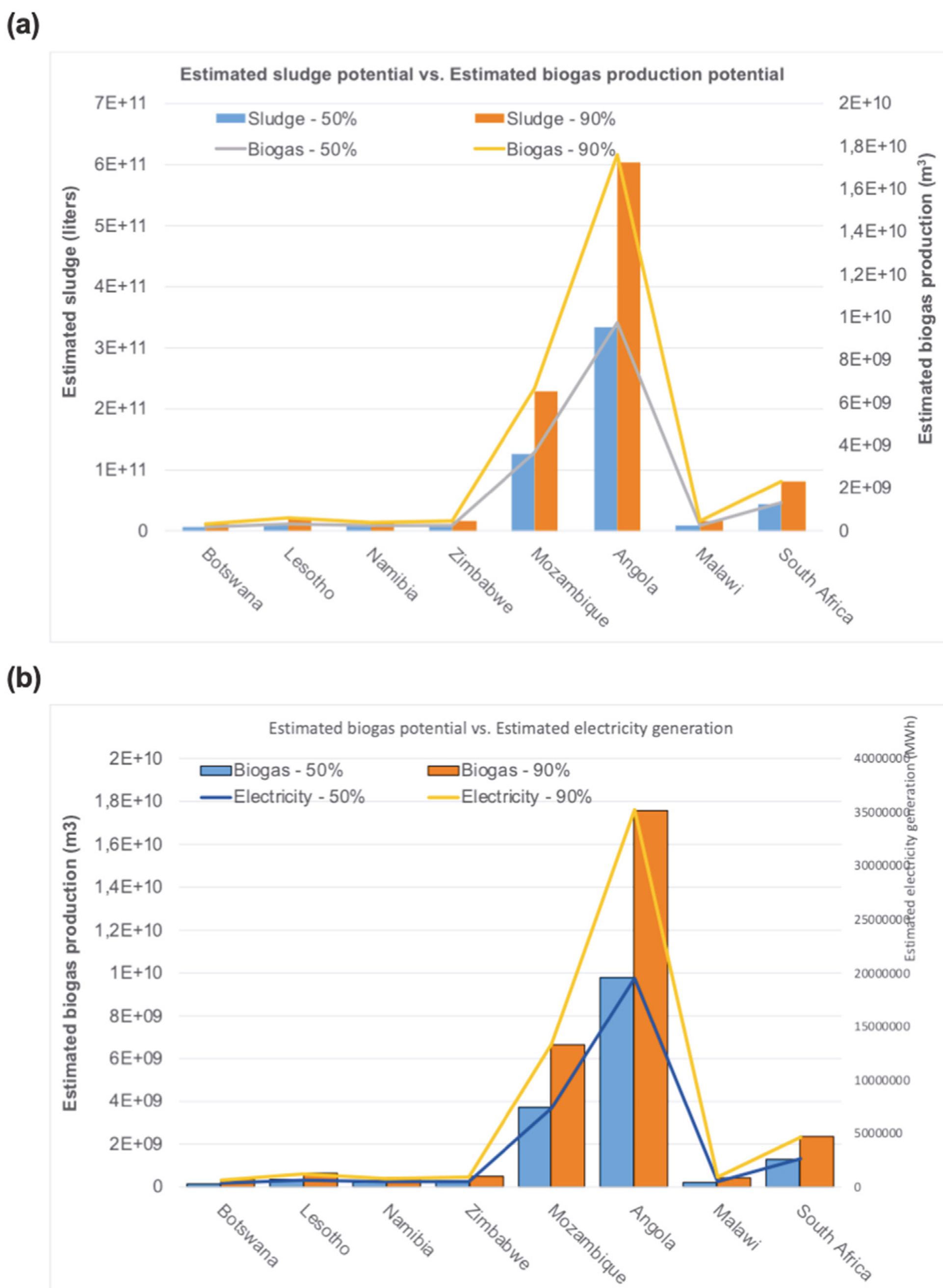

Figure 8. a–b Southern African Countries potential biogas and electricity generation from estimates of 50% and 90% wastewater derived from domestic freshwater withdrawals from World Bank data.

increasing their transfer into natural waterbodies. Furthermore, even when wastewater facilities exist, they are frequently underutilized or are not operating at full capacity (Harding et al., 2020; Edokpayi et al., 2017; Gyampo, 2012). Ultimately, these issues result in poor water quality for consumption by all living organisms in various ecological habitats, often with disastrous consequences. The prevalent problem of a lack of data related to wastewater generation is a major challenge in addressing wastewater management issues. One of the major factors impeding regional and global wastewater assessments, according to Sato et al. (2013), is a lack of up-to-date national data on wastewater generation, treatment, and use. They also emphasize the impact that the lack of such information has had on policymaking and further research that could have contributed to pollution reduction. Furthermore, they argue that a lack of information on wastewater generation is a barrier to national economic growth and development. The lack of credible data, particularly nationally relevant data, precludes considering wastewater as an economic resource. According to Cloete et al. (2010), the gaps in information and poor reporting surrounding industrial effluents are likely due to the fact that such information is regarded as sensitive and confidential by manufacturers within the industrial sectors that generate these questionable effluents. Companies may conceal information because of the potential health consequences and public outcry if such information became public. These constraints, however, are enabling in the under-development of research tailored to specific waste profiles. Additionally, the presence of these recalcitrant and often dangerous compounds in high concentrations in natural waterbodies leads to the observed accumulation in ecological food chains. Most recently, in 2018, the World Health Organization (WHO) and UN Habitat launched a project to report the global status of wastewater, which was published in 2021, after identifying a lack of information of wastewater status as a contributing factor to the slow implementation of SDGs related to clean water and the environment (WHO and UN-HABITAT, 2018). So far, their data only spans a year (2019–2020), and it was also stated in the report that data collection was hampered for most countries due to the COVID-19 pandemic bring to question it reliability. At least, a few years of coverage is necessary to identify a trend that assures validity and reliability of this data source.

7. Wastewater generation projections from World Bank 2017 freshwater withdrawals data

This review paper applies the data of water withdrawal obtained from the World Bank repository for 2017 (last update) for all Sub-Saharan countries (Table S1-S3) to demonstrate a simplified projection analysis of the possible wastewater generation. This can be readily employed for national policy making focused on infrastructural planning and development for these countries. It is hoped that this review encourages small and medium scale enterprises to identify this potential economic resource and thereby promote development of industries that will produce biogas from domestic waste and the mixture of industrial and domestic wastewater. It is also hoped that it will drive national and local policy frameworks around the development of integrated approaches for biogas production using wastewater sludge derived from the different commercial activities. This review paper uses data on water withdrawal from the World Bank repository for 2017 (the most recent update) for all Sub-Saharan countries to demonstrate a simplified projection analysis of potential wastewater generation (Table S1-S3). This can easily be used for national policy making in these countries focusing on infrastructure planning and development. It is hoped that this review will encourage upscale biogas production for Small, Medium and Micro Enterprises (SMMEs). However, in order to promote economic uptake, governments in Sub-Saharan Africa will need to act as economic drivers of commercial biogas production projects through the development of national and local policy frameworks that support public-private partnerships tailored to specific projects. Success also necessitates adaptability in developing different approaches for both decentralized and centralized agricultural and domestic waste management.

The World Bank data on freshwater withdrawals were chosen due to the current scarcity of direct-source data for wastewater generation for the three sectors (Table S1). It should be noted that data consistency is ensured because most countries' collection dates back to 1965 and includes freshwater withdrawals from all three sectors (agriculture, domestic, and industry), establishing a discernible trend. According to the World Bank report of 2015, the water usage attributed to industries in industrialized societies accounts for 41% of total global water demand. In comparison, only 3% of water demand in developing countries is used for industry, but with anticipated growth and development, this value is expected to rise (The World Bank, 2015). Nonetheless, there is potential and benefit in using waste from domestic applications in biogas production. Furthermore, given the large human population that generates this waste on a daily basis, waste profiles from this source are by far the most credible renewable resource, motivating its use in energy production. In contrast, industrial waste frequently contains a high concentration of metals. As a result, while it is also useful, it necessitates an initial precipitation step that is usually not required for domestic waste treatment. In most WWTPs domestic wastewater is combined with industrial waste treatment, such precipitates may contain significant amounts of metals that can be extracted and reused. The reclamation of metals from this process should be viewed as a long-term sustainable source of some useful metal, which should provoke the interest of small commercial enterprises involved in metal re-mining and extraction (Moghaddam et al., 2017; Hubbe et al., 2016). In this way, re-mining industrial effluents would not only sustain small businesses that previously targeted scrap metals for re-use; it would also reduce the circulation and mobility of these metals in the environment, thereby mitigating environmental pollution by reducing discharge and presence into waterbodies. Once adequate precipitation has occurred, the wastewater produced by industrial processes is relatively safe and can be mixed with agricultural and domestic waste for further degradation.

The estimates and projections are based on an understanding of two major precepts: (i) the distinction between water withdrawal and consumption; and (ii) the acceptance and established generation of sludge from all three types of wastewater previously described in this review. The following section of the review will concentrate on the latter precept. But to briefly clarify the first precept, it is critical to distinguish and apply the nuanced difference between water consumption and water withdrawal to support this paradigm. Water withdrawal is the process of redirecting water back to its natural source, such as a river or lake, often in an altered state, such as at a higher temperature. Consumption, on the other hand, refers to water that has dissipated during the industrial process, such as evaporation during thermal cooling, or that has been disposed of after pollution (as seen in petroleum production) or that has degraded as a result of contamination to the point where the physical and chemical properties of the water have been altered and no longer find application, necessitating its disposal (Kirchem et al., 2019; Rao et al., 2017). As a result of the inability to recycle or return such water to freshwater, water consumption contributes to water stress levels. The primary distinction between water and energy is that energy resources are infinite and can be replenished, whereas water resources are finite and cannot be replenished. The domestic wastewater projection derived from World Bank data for 2017 domestic freshwater withdrawal, as shown in Figures 5, 6, 7, and 8, is based on our understanding that water withdrawal eventually leads to water usage and the generation of waste water (see Table S3). Although the repository contains data for industrial and agricultural freshwater withdrawals, the focus on domestic water is based on the large volumes and higher organic loads with lower inhibitory compounds associated with this waste stream. However, both agricultural and industrial waste streams contain inhibitory compounds such as pesticides, synthetic fertilizers and toxic elements. As a result of the presence of inhibitory compounds in the latter sources, the ease of degradation is reduced, making domestic wastewater the most viable feedstock for eventual biogas production.

We investigated possibilities by deriving estimates for 50 %, 55 %, 60 %, 65 % 70 %, 75 %, 80 %, 85 %, and 90 % of wastewater from annual domestic freshwater withdrawals recorded for each country using World Bank 2017 freshwater status data (see supplementary Table S2). These ranges were chosen with the understanding that 50% is by far the most realistic minimum. Any lower estimate implies extremely high freshwater consumption with no chance of recovery, which is not an acceptable inference, especially given the stable trend of RIFWR data for most countries since 1965. Despite the observed water stress conditions, the RIFWR has remained constant in the majority of countries. In this paper, we only present the calculations for the lowest and highest (50 % and 90 %) as shown in Figures 5, 6, 7, and 8 for the various Sub-Saharan African regions. We demonstrate the potential biogas and electricity generation from wastewater sludge deposits in domestic wastewater using these two extreme range points. The projections revealed that in each region, there were countries with a significantly high potential for producing significant sludge from domestic waste, to the point where this material could be considered a credible feedstock for large-scale biogas production as shown in Figures 5, 6, 7, and 8. For example, Liberia, Uganda, the Democratic Republic of the Congo, and Angola may produce the most sludge that could be used for biogas and electricity generation in their respective regions. Furthermore, the Democratic Republic of the Congo has the potential to produce a minimum of 90 billion m^3 of biogas (approximately) from 50% estimated sludge projections, which can be used to generate nearly 178 million MWh annually. Similarly, the other potentially high-sludge-producing countries, Liberia, Uganda, Angola, and the Republic of Congo, produce 3–20 billion m^3 of biogas per year. This could generate between 3 and 30 million MWh of electricity per year. Even in countries with lower sludge production, such as Guinea, Nigeria, Sierra Leone, Madagascar, Tanzania, Rwanda, Kenya, Gabon, Central African Republic, Cameroon, Mozambique, and South Africa, most ranges are between 1 and 20 billion m^3 of biogas annually. With these values derived from minimum estimates of the lower limit of 50% wastewater generation from freshwater withdrawals, there is an implication that biogas quantities will increase with increased sludge projections from other wastewater derived values as is reflected in the 90% wastewater generation values.

8. Harnessing energy from wastewater – water reclamation and sludge production

For several decades, conventional wastewater treatment technologies based on physical and chemical treatment techniques have been used in Sub-Saharan Africa to improve the quality of wastewater discharged into the environment and prevent contaminated water from infecting nearby available clean water reserves (Voulvoulis, 2018; Rizzo et al., 2013; Ngo et al., 2002). Traditional treatment technologies, however, have flaws, such as the inability to make wastewater effluent suitable for downstream applications, particularly before discharge into nearby water bodies. Identifying water reuse projects is also uncommon in Sub-Saharan Africa (Stefanakis, 2016), with the norm being marginal wastewater treatment and discharge, with a reliance on dilution effects achieved through these discharges to mitigate the effects of toxic level concentrations in natural waterbodies. To avoid this practice, some countries have implemented innovative advanced technologies into the treatment regime in order to deliver higher-quality final effluent and achieve conservation through recycling and reuse (Seow et al., 2016; Ngo et al., 2002).

The removal of organic and inorganic, colloidal and suspended solids, dissolved compounds, biological constituents in the form of pathogens, potentially toxic compounds such as heavy metals or emerging pollutants (POPs), pharmaceuticals, endocrine disruptor chemicals (EDCs), and personal care products is the primary goal of advanced treatment technologies (Roccaro and Verlicchi, 2018; Galkina and Vasyutina, 2018; Seow et al., 2016; Asano et al., 2007). Recently, several technological alternatives that are either biological or physicochemical or hybrid of both, have been adapted to target specific pollutants and treat wastewater to a reusable standard (Galkina and Vasyutina, 2018; Stefanakis, 2016; Ngo et al., 2002). They include Advanced oxidation processes (Comninellis et al., 2008; Mishra et al., 2017), Membrane bioreactor (Schlosser, 2014; Fazal et al. 2015; Iorhemen et al. 2016; Stefanakis, 2016), Reverse Osmosis-based wastewater treatment (Trishitman et al. 2020; Anis et al., 2019; Pervov et al., 2018), Activated Carbon Filtration (Saleh et al. 2015; Azis et al., 2021; Kamal et al. 2019; Benstoem, and Pinnekamp, 2017) and Constructed Wetlands (Omandi and Navalia,

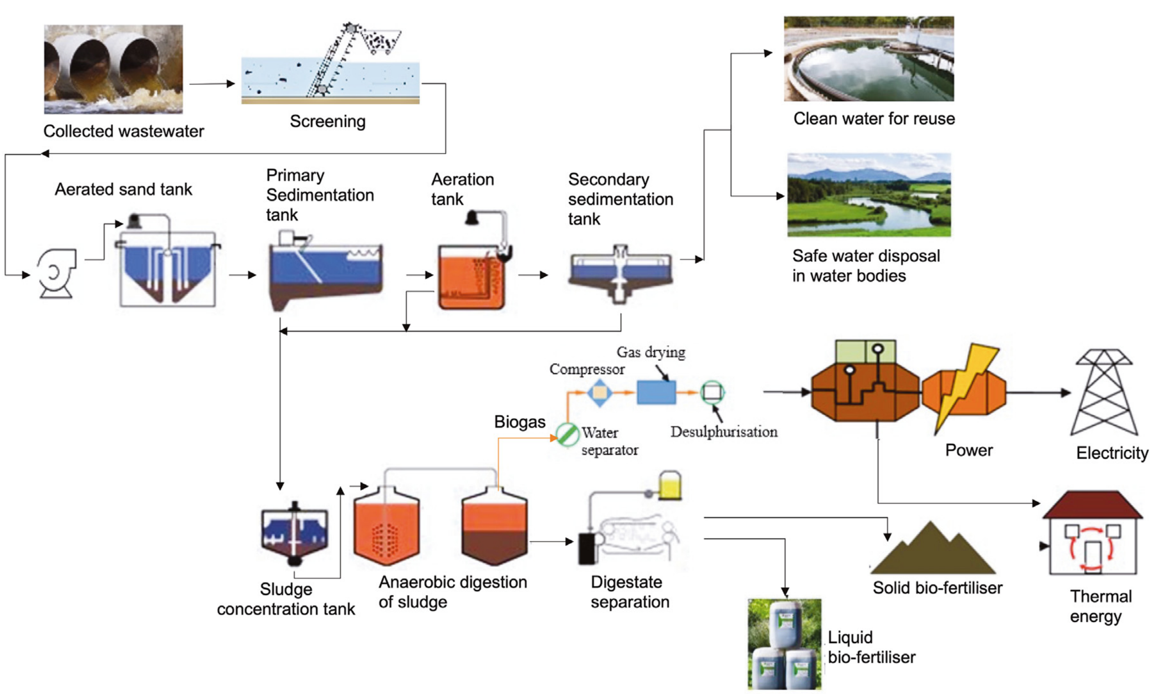

Figure 9. Conventional Wastewater Treatment Plant integrated with operational AD system for biogas production and electricity generation.

2020; Sehar and Nasser, 2019; Lamori et al. 2019; Vargas et al. 2017; Skrzypiec and Gajewska. 2017; Stefanakis et al., 2014).

Most wastewater treatment technologies and processes generate sludge, and the sludge quantities are substantial and significant when viewed through the lens of the economy of scales. Sewage sludge is a byproduct of wastewater treatment that is derived from agricultural, domestic, and industrial effluents as semi-solid residues. They are made up of inert solids and surplus biomass. The volume of sludge produced in a WWTP is only about 1% of the volume of influent wastewater to be treated (dewatered sludge is 0.5). The efficient management of any WWTP is dependent on the continuous removal of this sludge build-up in order to prevent accumulation and system fouling (Ambulkar and Nathanson, 2021; Foladori et al., 2010). Fresh sewage or effluent is typically received in a primary settling tank (see Figure 9), where approximately 50% of the suspended solid matter precipitates in a time frame estimated at 1.5 h (Ambulkar and Nathanson, 2021). Since anaerobic processes are not noticeable at this stage, this raw sludge is considered "fresh." This raw sludge is quickly moved to the sedimentation tank to prevent anaerobic digestion and methane buildup. Furthermore, the secondary treatment process produces sludge with high concentrations of aerobic bacteria and protozoa. This sludge is also removed through secondary settlement tanks. Both sludge streams are frequently combined and treated at elevated or ambient temperatures using phasic aerobic and anaerobic treatment processes to slowly encourage the proliferation of methanogenic microorganisms. Sludge anaerobic digestion produces biogas, and the treated sludge can be dried and disposed-off in a landfill. Cities such as Osaka, Japan, currently produce 6,500 tonnes of biosolid fuel per year from 43, 000 tonnes of sewage sludge. They had previously set a goal of recovering 30% of the energy generated by their black water, grey water, and storm water systems. This helps to power wastewater treatment facilities and contributes to the process's transition from a major energy consumer to energy neutrality and, eventually, net energy producers (Ghimire et al., 2021). The Australian Renewable Energy Agency (ARENA) (2021) described the national goal of energy sustainability and emphasized the significance of sewage sludge as an untapped energy reservoir. They established the Logan City Biosolids Gasification Project, with the goal of producing 34,000 tonnes of biosolids fuel per year from the 90 tonnes of sewage sludge produced daily. They also set an overarching goal of achieving carbon neutrality, with 70% of the energy saved in biosolids being recovered and reused by returning it to the facility. In the United States, Aries Clean Technologies will build the world's largest biosolids-only gasification plant in New Jersey, with the goal of converting 430 tonnes of biosolids fuel per day into 22 tonnes of biochar (Kiefer, 2021). The renewable energy generated by the system will be captured and applied to the facility (Sudborough, 2021). During normal operations, the facility will use a "no fossil fuel" strategy. The facility is intended to reduce GHG emissions in the future by reducing trucking miles and removing methane from biosolids landfill sites ahead of the COP 2030 deadline (Linden and Franklin, 2019).

Water reuse and reclamation initiatives are critical for economic and social development, as well as the reinforcement of economic circularity. This entails closing water and energy flow loops, as well as reducing resource inputs and outputs for more adept industrial processes (Hobson, 2020; Mabhaudhi et al., 2021). Strategic water reuse implementation is regarded as an important step toward achieving the Sustainable Development Goals (Mabhaudhi, 2019; Mabhaudhi et al., 2021). Angelakis and Synder (2015) emphasize the strong synergy between wastewater treatment and anaerobic digestion technologies in addressing the water-energy nexus collaboratively. Figures 5, 6, 7, and 8 apply the rational framework presented by Ambulkar and Nathanson (2021) of 1% sludge production from influent wastewater and thus assume this value for the purpose of estimating and deriving sludge quantities from the possible wastewater estimated from domestic freshwater withdrawal (billion m^3) in 2017. It is also understood that these values are most likely conservative and may be higher in practical environments and applications, but the goal of the exercise is to demonstrate the minimum potential value that can be derived from the waste stream on an annual basis in these countries with only minor retrofitting of existing wastewater treatment facilities and/or processes where decentralized systems are being utilized. Supplementary Tables S2 and S3, as well as Figures 5, 6, 7, and 8, show additional calculations and conversions to COD (kg) from which potential biogas production and electricity generation are calculated (MWh). Given the large datasets and values used in this review, derived COD values were used rather than volatile solids (VS) because the adaptability of COD to theoretical Biomethane Potential (BMP) calculations is more plausible (Filer et al., 2019; Nielfa et al., 2014).

A formula adapted from World Bioenergy Association (2013) was used for sludge calculations wherein:

The volume of sludge produced in a WWTP is presumed to be ≈ 1% (dewatered sludge is 0.5‰) of the volume of influent wastewater to be treated (Andreoli et al., 2007). Eq. (1) below was therefore used to estimate the sludge generated from wastewater.

$$\text{Volume of sludge } (l) \approx \text{ Volume of wastewater } \left(\text{billion } m^3\right) x \ \frac{0.01l}{10^{12}\text{billion } m^3} \tag{1}$$

A typical COD concentration in domestic wastewater sludge is often around 0.05 kg/L (Wan et al., 2016). On this basis, Eq. (2) was used to estimate the amount of COD derived from the estimated sludge.

$$\text{COD in sludge } (kg) \approx \text{Volume of sludge } (l) \ x\ 0.05 \left(\frac{kg}{l}\right) \tag{2}$$

On average, a kg of COD is estimated to produce about 0.35m^3 of methane (Sunada et al., 2012). This implies that assuming a methane content of 60%, the total biogas that can be produced per kg of COD would be given by Eq. (3):

$$\text{Biogas production } \left(m^3\right) \approx \text{COD in sludge } (kg) \ x\ 0.35 \left(\frac{m^3}{kg}\right) x \left(\frac{100}{60}\right) \tag{3}$$

According to the World Bioenergy Association (2013) and Kopetz (2013), 1 m^3 of biogas can generate approximately 0.002MWh of electricity. Eq. (4) was therefore used to estimate the amount of electricity generated.

$$\text{Electricity generation } (MWh) \ \approx \text{Biogas production } \left(m^3\right) x\ 0.002 \left(\frac{MWh}{m^3}\right) \tag{4}$$

Employing the same 50% estimates of wastewater (see Figures 5, 6, 7, and 8), at least nine other countries in Sub-Saharan Africa including Guinea, Liberia, Nigeria, Sierra Leone, Angola, Cameroon, Central African Republic, Gabon and Congo Republic can potentially produce at least ≥20 million MWh of electricity annually from biogas generated from sludge obtained from only their domestic wastewater. If ranges higher than 50% is used for these estimates, these values increase significantly.

9. Recommendations

Although most African countries use a decentralized wastewater management system, it is mostly regulated and managed by municipal governments via a centralized administrative system (Wang et al., 2014; Kazora and Mourad, 2018). In as much as the decentralized system is not a long-term solution, it is considered reliable and cost-effective, which is likely why it is currently preferred (Massoud et al., 2009). Furthermore, when we consider the cost, infrastructure, town planning, and stringent requirements for the construction, maintenance, and operation of centralized wastewater management, it becomes evident how difficult it is for most developing countries to adopt centralized systems at the present time (Oladoja 2017). Realistically, decentralized wastewater management meets the current needs of most developing countries by accommodating future growth and being adaptable to various wastewater treatment approaches. It is also appropriate for areas with low population densities and dispersed communities, as well as environmentally sensitive areas.

The current framework of decentralized disposal systems, with their archetypal off-site collection pipes and secondary networks, should be viewed as an opportunity for developing auxiliary structures and process additions that harness these existing paradigms for energy production, as shown in Figure 9. Tankers, for example, are frequently used to transport industrial effluents to WWTP sites. This opens up the possibility of preliminary waste sorting and separation, which can be accomplished more easily than in situations where they pass through sewerage network lines and become mixed with other wastewater. The separation and specific treatment of these industrial effluents provides maximum and long-term benefits. Firstly, the separation will allow for the sub-classification and grouping of specifically industrial effluents based on chemical profiles, allowing for the selection of best methods and options for pretreatment as well as the treatment of smaller volumes of such targeted wastewater containing extreme levels of concentrated toxic elements. Second, if this waste separation strategy based on chemical composition is the employed approach, it is possible to achieve the pH of 9.5 (Charerntanyarak, 1999) required for optimal precipitation treatment while reducing the cost of procuring large quantities of the compounds needed such as calcium hydroxide (lime), sodium hydroxide (caustic), or sodium sulphide, depending on the specific effluents identified for treatment. The current trend of combining industrial effluents with domestic wastewater for treatment has been observed to contribute to the challenge of cost as a deterrent. Due to the high costs associated with mixed and consequently increased volumes, the precipitation step of treatment is frequently avoided (such as domestic and industrial wastewater combinations). Therefore, it is recommended that precipitation step treatment should be used for only industrial effluent volumes, which are typically quite manageable quantities as compared to domestic wastewater. The focus on only industrial effluents for precipitation treatment will address the challenge of limitation brought on by rising costs of chemicals, which has been identified as a deterrent to the inclusion of this step in recent times at most Sub-Saharan African treatment facilities. Although other methods can be used, chemical precipitation is regarded as the least time-consuming option for heavy metal removal (Pohl, 2020). Furthermore, its skill requirements and training for management and labor application are minimal. This is the reason it has remained the preferred option for metal removal.

Furthermore, even as a biostimulation strategy for nutrient supplementation to improve microbial biomass proliferation, the practice of mixing industrial and domestic waste at WWTPs provides little benefit (Ijoma et al., 2019). This is due to the practice's failure to account for elemental ratios in balancing the osmotic shock that is likely to occur in living cells exposed to such high concentrations as will be encountered in large-scale wastewater treatment. Such concentrations are usually detrimental to microbial biomass growth in any system unless the optimization or balance of elements present is considered or adjusted. Moreover, microbial degradation focuses primarily on the organic components of the waste stream, and living cells and biomass frequently merely absorb any toxic elements present via physical processes of adhesion and adsorption. Even when required in living cells for metabolic activities, most of these elements are only required in trace amounts. This means that larger amounts are only temporarily removed by biosorption and will eventually accumulate in aquatic environments after the absorbing microorganisms die and lyse. As a result, chemical precipitation of industrial effluents containing high concentrations of elements and metals is preferable before combining the liquid waste with domestic wastewater. The separated industrial precipitate (sludge) can be collected and extracted for economically important metals, which can then be refined for reuse in various industries. Small and medium-sized businesses should consider sludge from industrial effluents as a potential raw material and platform commodity. Furthermore, the separation allows for the targeted treatment of specific chemical profiles, which will address the recalcitrant nature of some compounds present in these effluents. It will also enable the use of specific strains of microorganisms that have been adapted for biological treatment, ensuring that significant levels of these recalcitrant and toxic elements do not eventually end up in natural waterbodies.

The incorporation of anaerobic digesters and biogas storage and collection infrastructures into existing WWTPs, followed by the conversion of this biogas into electricity and heat energy, effectively ensures a circular economy. Following the production of biogas from anaerobic digestion, purification and liquefaction steps can be under-taken. Methane content after AD is typically between 45 and 75 %, with the remainder being CO_2 and other gases useful for a variety of applications; scrubbing processes can be used to achieve higher quality methane gas (Andriani et al., 2014; Angelidaki et al., 2019). Although the inclusion of the scrubbing process incurs an additional cost (Nguyen et al., 2021), when considering the long-term benefits, particularly to the environment, it is worthwhile toward our goal of environmental pollution reduction and carbon neutrality. Furthermore, the inclusion of this additional step is motivated by the expanded range of applications that are possible with purer biomethane.

It is critical to understand that biogas production from wastewater should be viewed not only as an alternative renewable energy source within the green economy, but also from an ethical standpoint of saving the environment from further degradation. Moreover, it provides opportunity to achieve carbon neutrality within WWTPs and has associated economic growth. However, legislative reforms and the establishment of policies and frameworks to support small and medium-sized enterprises and start-ups willing to collaborate with local municipalities in the task of managing business opportunities around WWTPs in these countries are also required to facilitate the rapid progress and implementation of these integrations. It is important to note that any credible business model will necessitate private-public collaboration and the shared use of existing infrastructure to drive fiscal viability, as this will reduce impediments that have so far slowed the effective diffusion of biogas production technologies in this sector. The conversion of biomass and municipal waste into clean energy closes the economic loop and assists communities in their transition to circular economies. Adoption of large-scale biogas technology will also contribute to the decarbonization of the industrial, domestic, and agricultural sectors (D'Adamo et al., 2021) and the long-term preservation of the environment (ENGIE, 2021).

10. Conclusion

A critical assessment of the water-energy nexus in the majority of Sub-Saharan African countries reveals the urgency of a shift in strategies regarding water resource management. This is critical to ensuring the long-term viability of potable water. Harnessing the potential of sludge for energy and even elemental resources not only provides opportunities for economic growth, but it also addresses the issue of pollution, which is frequently the result of inadequate wastewater treatment and discharge from WWTPs. As a result, this strategy is required. Although there is a lack of data on wastewater generation from agriculture, domestic, and industrial sectors, data on freshwater withdrawals can be used to estimate these values and plan infrastructure development, as well as integrate existing systems, to help Sub-Saharan Africa achieve the relevant SDGs of clean water, energy, and economic growth. The use of municipal waste sludge as a resource can be considered renewable feedstock for several aspects of green technology that can help transition wastewater treatment plants toward a circular economy and help sustain the life of these public works through revenue generated from efficient sludge management. It is therefore prudent for Sub-Saharan African countries to capitalize on this readily available source of energy and improve livelihoods through waste generated by households and industries.

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Author contribution statement

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