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An Overview of the Technological Advancement of Wastewater Treatment for Effluent Reuse in South Africa: a Meta-Analysis

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Abstract

South Africa's water resources have experienced significant negative effects resulting from poor quality effluent, posing a substantial threat to public health. The main aim of this study was to evaluate the existing technological condition of wastewater treatment and sanitary infrastructure in South Africa. The rationale for conducting this study was derived from the occurrence of a recent cholera outbreak. The research employed meta-analytical techniques to review information from sources such as published journals and reports from databases such as PubMed, Science Direct, Springer and Google Scholar to investigate the impact of technological advancements in wastewater treatment and the condition of the state sanitary infrastructure in South Africa. The data was organized, summarized, and presented using basic descriptive statistics in Microsoft Excel 2019. The findings of the study reveal that ponds and lagoons have emerged as the predominant wastewater treatment technology in South Africa, with Activated Sludge technology being the second most commonly employed method. The current infrastructure is insufficient to manage the escalating volume of wastewater and the heightened water quality standards that arise from population growth and expanding industrial operations. Moreover, our study indicates that despite substantial financial allocation made by the government for the enhancement and restoration of infrastructure, the effective management of wastewater remains a persistent issue. South Africa should explore and allocate resources for emerging technologies for wastewater treatment such as membrane technology and membrane bioreactor technology, which offer advantages such as treatment of high biomass concentrations, and smaller space requirement compared to traditional systems.

Other benefits of these emerging treatments include lower hydraulic retention time, high effluent quality lower biosolids and higher volumetric loading. These advantages are more applicable in South Africa, since they require a smaller amount of area compared to other conventional treatment technologies, as rapid populating growth, coupled with urbanization, has led to a shortage of available land suitable for the construction of new wastewater treatment systems to accommodate development.

Keywords: Effluent Quality, Green Drop Certification Program, Wastewater Treatment Plant, Sanitary Infrastructure, Water Services, Advanced Wastewater Treatment, Wastewater Reuse.

1. Introduction

South Africa is currently faced with severe water challenges which are attributed to many factors ranging from prolonged drought periods to poorly treated wastewater, in addition to the country being a semi-arid country (Mema, 2010; Phungela et al., 2022). Moreover, the impact of climate variability places serious constraints on the country's water security (Amoah et al., 2020). South Africa's population is growing rapidly which translates to increased demand for water services for industrial, agricultural, and domestic water uses. There are around 850 municipal wastewater treatment plants[1] in South Africa, along with sewer networks and sewage pump stations that handle wastewater every day (Department of Water Affairs[2], 2009). Rapid population growth and urban migration have an impact on wastewater treatment infrastructure and sanitation systems since they cause these infrastructures to operate above their capacity (Masindi and Dunker, 2016). Municipality wastewater services are widely regarded as far from acceptable when compared to required national standards and international best practices (DWA, 2009).

Hence, several reports and research studies indicate that the vast majority of South Africa's WWTP are inadequate, especially in townships and informal settlements (Mema, 2010; Amoah et al., 2020; Phungela, 2020; Gqomfa et al., 2022; Phungela et al., 2022; Maphanga et al., 2022). Poor maintenance and refurbishment of WWTP infrastructure have reduced the performance of the plants to effectively remove pollutants (Mema, 2010; Sibanda et al., 2015; Phungela et al., 2021).

Moreover, the WWTPs are operating beyond their designed capacity, which compromises the treatment process. It is for this reason that there are continuous water services delivery failures across the country today, i.e., Hammanskraal cholera outbreak (Masindi and Dunker, 2016; Kretzmann, 2022). Furthermore, the 2013 report highlighted how insufficient planning, execution, and management of existing infrastructure have led to large volumes of untreated sewage flowing into water resources, non-functional unit processes within the treatment work, and pipe leaks.

Ntombela et al. also found that only 50.4% of WWTP in South Africa scored above 50% in the 2012/13 Green Drop audit, indicating that 49.6% of the overall WWTPs (409 WWTP) received a purple drop status (less than 30% performance). DWA (2013) reported that 121 WWTPs were at critical risk and should be monitored as "hot spots" to ensure that compliance and risk mitigation are accelerated. At least 19 incidents of wastewater overflowing into water bodies were reported in April 2015 (Ntombela et al., 2016).

Furthermore, the 2022 Green Drop report shows that 334 of 850 municipal WWTP are in a critical state, reaffirming the 2013 report. Approximately half of all wastewater treatment facilities in South Africa are ineffective at treating wastewater to acceptable standards. This decline is occurring at both the treatment and sewer collection systems, the report states (Green Drop Report, 2022). Not only are WWTPs failing to properly treat sewage before releasing it back into the environment, but a significant amount of sewage is leaking into the environment before it even reaches treatment plants (Edokpayi et al., 2015).

Due to overcapacity, ageing infrastructure, and inadequate maintenance, as well as a lack of technical capacity, effective treatment of wastewater is not achieved. In general, South Africa's wastewater treatment situation reflects the country's broader challenges in terms of access to basic services and infrastructure as well as the need for continued investment and innovation to address them (Edokpayi et al., 2015).

As a result of failing WWTPs and sanitary infrastructure, South Africa's water resources have been impacted severely due to poor quality effluent discharge (Mema, 2010; Iloms et al., 2020). Several studies have been undertaken in South Africa, linking poor quality of water resources to failing wastewater treatment and sanitary infrastructure (Abia et al., 2015; Amoah et al., 2020; Phungela et al., 2021; Phungela et al., 2022).

Furthermore, Phungela et al., (2022) assessed the impact of wastewater treatment plant effluent on a particular water resource, and it was noted that discharged effluent was impacting the overall quality of the river, and the leading factor towards poor quality effluent was attributed to failing wastewater treatment infrastructure and associated components such as dysfunctional aerators and disinfection equipment, as well as failing pumps. Discharge of poorly treated effluent caused by dysfunctional WWTPs has an adverse

[1] Wastewater Treatment Plants (WWTP)
[2] Department of Water Affairs (DWA)

impact on both the receiving environment and human health because wastewater consists of a variety of pathogenic microorganisms such as Vibrio cholera, Salmonella spp, *E. coli*, Giardia, Cryptosporidium, which are notable for causing diseases and threatening public health (Chinyama et al., 2016; Bunce et al., 2018).

Edokpayi et al. (2017) highlight that since wastewater consists of various classes of pathogens which are capable of causing diseases of various magnitudes in humans, it is thus important that wastewater treatment be efficient. Edokpayi et al. (2017) further note that unlike some of the environmental impacts that can take longer before manifesting due to the discharge of poor wastewater effluent treatment, pathogens present in the effluent cause an immediate negative impact on the people using contaminated surface water resources for domestic, agricultural and recreational purposes. This is evidenced by several episodes of disease outbreaks such as cholera, that have been reported previously in various provinces of South Africa, with wastewater treatment effluent as a major contributor.

In light of the studies that were conducted, it is evident that rivers such as Vaal River, Juskei River and Klip River are impacted by poor wastewater treatment and sanitary infrastructure (Iloms et al., 2020; Kamika et al., 2021). According to an inquiry conducted by the South African Human Rights Commission in 2021, the Vaal River catchment is now polluted beyond acceptable levels mainly as a result of inoperable and dilapidated WWTPs that have failed to properly treat wastewater prior to discharge.

The cost and difficulty of treating water for drinking (and other purposes) increase as water sources become more polluted (Jordaan and Bezuidenhout, 2013). For example, a study conducted by Winter and Carden, discovered that in 2014, sewage had contaminated a small rural town named Bloemhof, which resulted in a tragic loss of lives. In addition to the 18 infant deaths, over 200 people were hospitalized (Winter and Carden, 2022).

Throughout the literature search, it was found that no study has characterized WWTPs in South Africa based on the different types of technologies being used. However, a limited study has looked at how different technological advancements help improve wastewater treatment. Therefore, this study seeks to assess and characterize wastewater treatment technologies and sanitary infrastructure in South Africa, and their general performance.

1.1. South Africa's legislative framework governing water services provision

Proper water services infrastructure provision was historically prioritized for the minority white population and their respective residential and business areas, whereas black residential areas were not properly serviced, which was perpetuated by racial policies implemented by the then apartheid government (Kidd, 2011). During that period, the country's water and wastewater infrastructure only focused on catering for a population of about 6 million, which included a majority of affluent whites, a portion of people of color in segregated urban townships, and the needs of the highly productive industrial and agricultural sectors (Kidd, 2011).

After the dawn of democracy in 1994, legislative reforms were made, which included the promulgation of the Water Services Act in 1997. The provision of water services in South Africa is now guided by the Water Services Act (Act 108 of 1997) as the primary legislative tool, which aims to realize the right of access to basic water supply and basic sanitation within the country, including the previously marginalized groups. The water services provision function is decentralized to local government (local and district municipalities) as Water Services Providers[1] and Water Services Authorities[2] and are tasked, amongst other things, to develop, operate and maintain associated water services infrastructure (Harris and Vermeulen, 2011).

The Water Services Act provides an obligation to municipalities as WSAs to provide detailed measures and plans in its Water Services Development Plan[3] to realize the right to basic water supply and sanitation. The WSDP, according to the Water Services Act (Act 108 of 1997), should contain, amongst other things, the estimated capital and operating costs of water services, financial arrangements for funding water services, the operation, maintenance, repair, and replacement of existing and future infrastructure. Municipalities within the country are furthermore mandated in terms of the Municipal Systems Act to develop an Integrated Development Plan[4] which guides all development within the municipal area, clearly highlighting short-term and long-term developmental needs and associated financial implications.

Dlamini and Reddy (2018), outline that an IDP serves as a development framework for the municipality, assisting with the acceleration of service delivery by providing an instrument where development should be prioritized within the local government. Therefore, the IDP of the municipality needs to incorporate the WSDP, as currently, there is insufficient representation or incorporation of major components of the WSDP into the IDP, which is evidenced by the misalignment of the implemented services with the desired outcome.

[1] Water Services Providers (WSPs)
[2] Water Services Authorities (WSAs)
[3] Water Services Development Plan (WSDP)
[4] Integrated Development Plan (IDP)

Table 1. Wastewater limit values applicable to the discharge of wastewater into a water source according to the National Water Act (DWAF, 1999)

Substance /Parameter	General limit	Special limit
Faecal coliforms per 100ml	1000	0
Chemical oxygen demand (mg/L)	75	30
pH	55-9.5	5.5-7.5
Ammonia (ionized and un-ionized) as Nitrogen (mg/L)	3	2
Nitrate/Nitrite as Nitrogen (mg/L)	15	1.5
Chlorine as free chlorine (mg/L)	0.25	0
Suspended solids (mg/L)	25	10
Electrical conductivity (mS/m)	70 mS/m above intake to a maximum of 150 mS/m	50 mS/m above background receiving water to a maximum of 100 mS/m
Orthophosphate as phosphorus (mg/L)	10	1 (median) and 2.5 (maximum)
Fluoride (mg/L)	1	1
Soap, oil or grease (mg/L)	2.5	0
Dissolved arsenic (mg/L)	0.02	0.01
Dissolved cadmium (mg/L)	0.005	0.001
Dissolved chromium (VI) (mg/L)	0.05	0.02
Dissolved copper (mg/L)	0.01	0.002
Dissolved cyanide (mg/L)	0.02	0.01
Dissolved iron (mg/L)	0.3	0.3
Dissolved lead (mg/L)	0.01	0.006
Dissolved manganese (mg/L)	0.1	0.1
Mercury and its compound (mg/L)	0.005	0.001
Dissolved selenium (mg/L)	0.02	0.02
Dissolved zinc (mg/L)	0.1	0.4
Boron (mg/L)	1	0.5

1.2. The need for wastewater treatment and sanitary infrastructure: legislative requirement governing effluent quality water resources protection

The National Water Act defines water use as not only including consumptive uses but also actions that contaminate or have the potential to pollute or degrade a water resource (Republic of South Africa, 1998). These activities involve releasing waste or water with waste into a water source through a pipe, canal, sewer, sea outfall, or other controlled conduit by an authorized person responsible for treating or disposing of waste or water containing waste, pending approval from the person in charge of the conduit. Authorization from the competent authorities is required to engage in the water use activities indicated above, which can be obtained through a Water Use License[1] or a General Authorization[2] for water usage. A water user is granted permission to discharge wastewater effluent into a water resource with certain conditions, guidelines, and water quality limits that must be followed during the activity. Wastewater presents a substantial pollution risk to water resources and the ecosystem, so its discharge and management need to be regulated (Okoh et al., 2007).

The National Water Act stipulates limits for certain parameters, as shown in Table 1 below, of wastewater limit values applicable to the discharge of wastewater into South Africa's water resources, based on South

[1] Water Use License (WUL)
[2] General Authorization (GA)

Africa's legal framework on effluent discharge.

1.3. Green drop regulatory program: a regulatory tool for wastewater management and governance

Water resources are primarily affected by the quality of effluent discharged into them if treatment plants are not performing effectively; for example, if a plant fails, if it is not maintained adequately, or if it runs beyond its design capacity. The Green Drop Regulatory Program, an incentive-based regulation initiated by the Department of Water and Sanitation[1] in 2008, has demonstrated the magnitude of maintenance challenges in South Africa. The Green Drop program is essential for increasing water system awareness and transparency in South Africa. The program performs annual audits of sewer networks, pump stations, and treatment systems, but does not evaluate sanitation or informal settlements where untreated sewage enters the environment. The Green Drop audit identifies risks at each wastewater treatment facility, but addressing deficiencies and failures requires more complex measures by different stakeholders.

The report evaluates each of the nation's 995 wastewater treatment plants, with the most recent report published in March 2022. These evaluations are essential for monitoring South Africa's wastewater systems, which treat wastewater and release it into rivers in a safe manner. The report is indispensable for monitoring South Africa's water systems, which treat sewage and release effluent that has been tested for microbial and chemical quality.

Wastewater Treatment Systems receive a final Green Drop score based on their performance in multiple key performance areas, with effluent quality compliance, technical management and financial management carrying the most weight per criterion, (20%, 20% and 30% respectively). Each plant is assigned a score, with a score above 90% indicating an excellent wastewater system and a score below 31% indicating ineffective facilities. The report highlights the neglect of seven of the nineteen municipalities, with some plants, such as the Gariep Dam wastewater treatment plant, having been abandoned. One in three wastewater treatment plants was deemed critical in 2022 (Green Drop Report, 2022).

Municipalities with dysfunctional plants were required to submit a corrective action plan within 60 days of the publication of the Green Drop Report. Nonetheless, only 19 municipalities, representing 82 of the 334 dysfunctional systems, have submitted the necessary plans, indicating a lack of progress in addressing these problems. Data from the DWS indicates that even wastewater treatment facilities with scores of 90 per cent or higher pollute the environment. According to the report, effluent quality must meet 90 per cent of the authorized limits for each category. The minimum compliance levels are specified in the authorization issued by the DWS for each wastewater treatment facility.

2. Materials and methods

2.1. Literature search strategy

This paper used secondary data from the existing literature across South Africa, which strictly included peer-reviewed and published journal articles from databases such as PubMed, Science Direct, Springer and Google Scholar; Government reports such as Green Drop Reports to develop a metanalysis approach for an overview of the technological advancement of wastewater treatment and state of infrastructure. In addition to the report published by the DWS, pertinent information published in journal articles was deemed essential for developing the meta-analysis. Consequently, they were included in the current study. During the literature search, English peer-reviewed articles and pertinent provincial and national government reports were reviewed to develop the current meta-analyses. Extensive Green Drop Project Reports, published papers, and government websites were mined for data used in the evaluation and assessment that subsequently informed the current study. Scientific databases such as Google Scholar, Semantic Scholar, Sage, and Research Gate were primarily used to conduct electronic searches to validate the findings of government reports. Variables such as (a) South African WWTP, (b) Green Drop Report, (c) State of wastewater treatment in South Africa, and (d) South African Wastewater provincial status report were used to narrow the search for relevant literature on WWTP.

These thematic inquiries were conducted throughout the nine South African provinces. Both Madonsela et al. (2023) as well as Grangxabe et al. (2023) have previously employed a similar framework adopted by the current study. Additional searches were sourced through the reference lists of substantial publications, as is the standard procedure according to Mkwanazi et al. (2021), to cover a broad spectrum of articles and provincial government reports from across the country. This practice is known as the second search, which employs the snowball method from the initial list of relevant references. The limitations of the methods of literature search include the search for published government and academic literature that is restricted to South African parameters.

2.2. Data analysis

Microsoft Excel 2019 was used for data capturing and analysis. Microsoft Excel 2019 simple descriptive statistics were used to organize, summarize, and present data, as recommended by Keller et al. (2014). The

[1] Department of Water and Sanitation (DWS)

practice of using simple descriptive statistics allows a researcher to quantify and describe the basic characteristics of a data set (Allen, 2017). Thus, graphs as well as the frequency distributions, were utilized to present the findings of the current study. For analysis, all of the mined WWTP data that was important to the current study were categorized based on their South African provinces. This process facilitated the generation of graphs and numerical values.

3. Results and discussion

3.1. Overview of the factors affecting the key performance of wastewater treatment plant systems

As part of the National Water Act (Wastewater limit values), the performance of WWTP is mainly measured on pollutant removal ensuring compliance with regulations for final effluent discharge. In Fig. 1, the performance of a wastewater treatment system is categorized based on the following aspects: effluent and sludge compliance, technical management, environmental management, and financial management. Based on the results in Fig. 1, effluent and sludge compliance and technical management are the two key performance areas which are accountable for the overall low compliance score amongst wastewater treatment systems in South Africa. Effluent and sludge compliance key performance area, includes compliance with effluent and sludge to stipulated quality limits and compliance with monitoring requirements. In contrast, technical compliance, a key performance area, includes wastewater treatment design capacity management, compliance with process audit requirements, inspection, and management of sewer lines.

Fig. 2 highlights the number of overloaded wastewater treatment systems per province, and from the results, it is observed that Eastern Cape has the highest hydraulically overloaded wastewater treatment system, followed by Western Cape Province, which means that the system is operating beyond its design capacity. Hydraulic overloading is mainly caused by a rapid increase in the inflow of wastewater into the plant due to factors such as population growth and urbanization, whereas there is no capacity upgrade of the existing infrastructure (Teklehaimanot et al., 2015).

An evaluation of WWTP's performance is crucial for long-term, cost-effective wastewater management. Although nearly every province fell into the dysfunctional category, only one submitted the required plan. The cost of failure is, unsurprisingly, not inexpensive when it comes to repairing this degree of deterioration. The performance assessment system of urban WWTPs was designed to measure the plant effectiveness and reliability, i.e., compliance over time with quality requirements of the treated water, and the efficiency (in terms of resources utilization) and sustainability (economic and environmental), by utilizing performance indicators and performance indices in a continuous improvement approach.

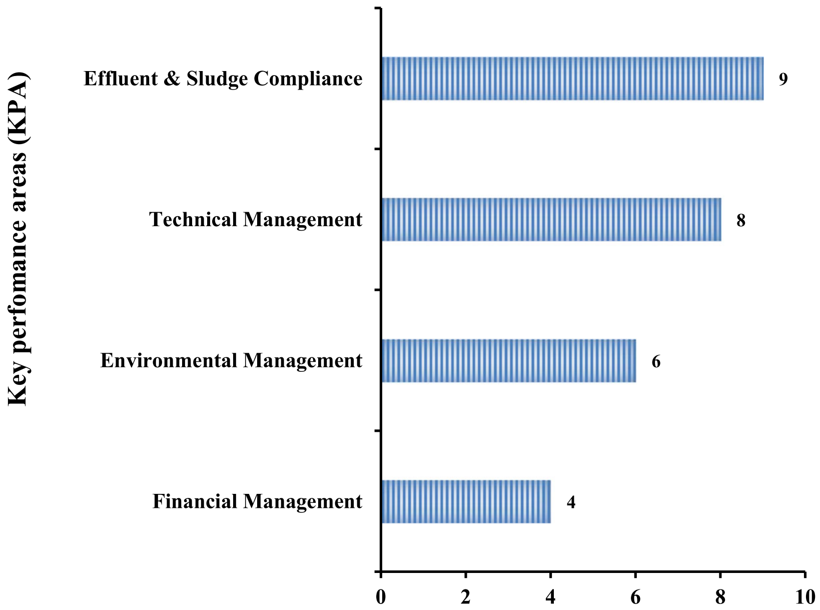

Fig. 1. Number of provinces not compliant with Green Drop KPAs

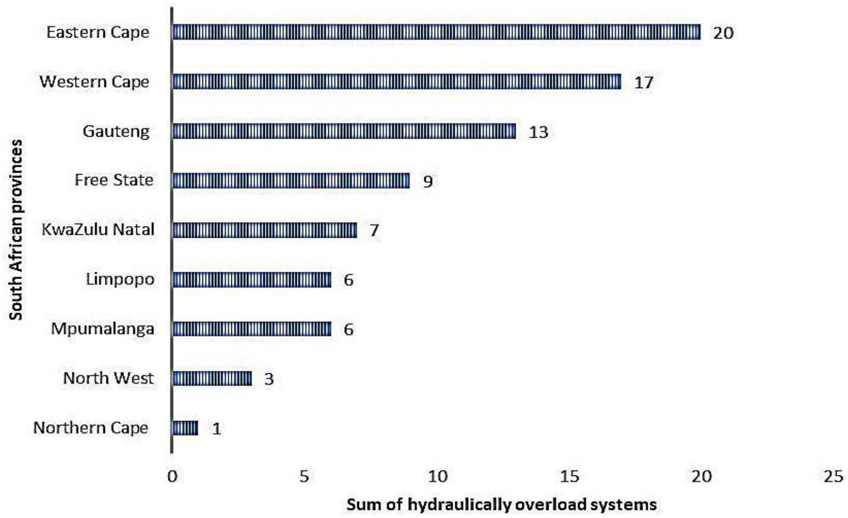

Fig. 2. Number of hydraulically overloaded wastewater treatment systems per province

3.2. Wastewater treatment technologies prevalent in South Africa

Fig. 3 and 4 show the different technologies used in WWTP for both effluent and sludge treatment across South Africa. The use of ponds and lagoons is a popular wastewater treatment technology with at least 303 plants using this technology. The second highest is the AS (Activated Sludge) with 186 plants relying on this technology (Fig. 3). The use of ponds and lagoons requires a large surface area for their construction compared to other treatment technologies, Edokpayi et al. outline that the main reason ponds and lagoons are prevalent as the applied wastewater treatment technology, especially in South Africa, is their design simplicity, low cost associated with construction and maintenance, and the use of low skilled operators. These ponds, if properly designed, operated and maintained, are capable of yielding compliant effluent that does not impact receiving water resources (Edokpayi et al., 2021).

However, it is important to note that waste stabilization ponds[1] as a wastewater treatment technology are recommended for communities with a population of less than 5000, due to their hydraulic and organic design capacity. Most of South Africa's WSPs were built 30-40 years ago, servicing a population of less than 5000. However, with rapid population growth, these systems are operating beyond their design capacity, compromising effluent quality.

Activated sludge is the second most applied wastewater treatment technology in South Africa, due to its ability to treat wastewater from areas with larger populations (metropolitan, large towns with industries), and its ability to effectively remove pollutants of concern such as organic matter, nitrogen, and phosphorus. Most activated sludge plants in South Africa follow a simple configuration of a bioreactor with three zones (aerobic, anaerobic and anoxic), with oxygen transferred mechanically using surface aerators in the aerobic zone. Activated sludge systems are, however, associated with high operating costs due to their energy intensive nature compared to other treatment technologies, accounting for most of the municipality's electricity consumption (Siatou et al., 2020).

A study undertaken by Molinos et al. (2018) highlights that conventional activated sludge treatment technology consists of a higher energy intensity of an average of 0,631 kWh/m^3 of wastewater treated when compared to other treatment technologies such as extended aeration (0,562 kWh/m^3), biofilter (0,55 kWh/m^3), and rotating biological contactor (0,40 kWh/m^3). The energy intensive nature of this system is due to the oxygen transfer methodology applied, which is mostly surface aerators consuming about 67 % of the total electric energy supply of the plant (Siatou et al., 2020).

In contrast to ponds and lagoons, activated sludge treatment systems are complex with regards to electrical and mechanical components associated with them, hence skilled personnel are required to operate and maintain them. A study by Molinos et al. (2018) further highlights that, even though an activated sludge system generally has a higher energy intensity, currently many countries prefer using it due to its treatment efficiency with regards to COD and suspended solids, which the study notes have removal efficiencies of 92% and 89%, respectively, which is higher than that of biofilter, rotating biological contactor and extended aeration.

Phungela et al. (2021) highlighted that South African WWTPs are mostly dysfunctional and are unable to effectively treat wastewater due to poor maintenance of associated mechanical and electrical equipment.

[1] Waste Stabilization Ponds (WSP)

Typically, sludge treatment and management processes include sludge thickening, sludge stabilization, conditioning and dewatering prior to final disposal. Not all WWTPs in South Africa comprise all these processes. Thermal Drying Beds is the most commonly used sludge treatment method with 256 plants using it, followed by sludge lagoon with 99 plants utilizing this sludge management technology (see Figs. 4 & 5). Thermal Drying Beds are generally favored compared to other sludge treatment technologies due to the low cost of operation and maintenance associated with them. The effectiveness of thermal drying beds to condition sludge is, however, dependent on several factors such as the nature of the sludge, weather and climatic conditions, height of applied sludge and solids content of the sludge (Elbaz et al., 2020).

3.3. Wastewater treatment technological innovations that can be considered in South Africa

South Africa's increasing population, rapid urbanization and increasing industrialization, coupled with changing climatic patterns have a negative impact on the current ageing wastewater treatment and sanitary infrastructure, thus leading to environmental degradation and potential risk to public health (Asoka et al., 2013; McDonald et al., 2014).

Statistic South Africa, a government department responsible for undertaking the country's statistical analysis undertook a census in 2022 and revealed that between 2011 and 2022, the country's population increased from 51. 7 million to 62 million, with a growth rate of about 1.8%, with Johannesburg, Durban and Cape Town being cities with the highest population, accounting for almost 23% of the total population (Stats SA 2023). It is estimated that approximately 80% of the country's population will be living in urban areas by 2050. With such population growth and rapid urbanization, massive strain is therefore exerted on the country's wastewater treatment and sanitary infrastructure. Rapid industrial growth, similar to the trajectory that South Africa is taking, can also place massive stress on the current wastewater treatment and sanitary infrastructure, both quantitatively and qualitatively if not properly planned.

A study undertaken by Iloms et al. (2020) revealed that most of the effluent emanating from industries in Vaal (South Africa) consists of high concentrations of toxic heavy metals and a cocktail of emerging contaminants contributing to high organic loads. These industrial effluents discharged into conventional municipal WWTPs are hardly treated efficiently since current conventional municipal WWTPs are not designed for the removal of heavy metals, emerging contaminants and high organic loads (Sylwan and Thorin, 2021; Dubey et al., 2023).

Partially treated or untreated industrial effluents have a negative impact on the receiving environment. Climate change is another factor that has been noted to significantly impact the overall functionality of wastewater treatment and sanitary infrastructure. A study by Singh and Tiwari (2019) noted that changes in regional temperature, precipitation patterns, rising sea levels, and storm related changes caused by climate change will lead to a significant increase of untreated wastewater. The effects of climate change towards wastewater treatment and sanitary infrastructure are mostly noted in municipalities of urban nature, whereby the degree of damage of such infrastructure depends on the geography, and demography (Major et al., 2011; Singh and Tiwari, 2019).

Heavy precipitation induced by climate change causes malfunctioning of WWTP since rapid stormwater runoff finds its way into sewer lines, combining with sewage overflows, and leading to inadequate wastewater treatment, and environmental pollution; other negative consequences may include percolation of sewer water into groundwater, intrusion of foreign pollutants into WWTP, flooding of pump stations and increased sediments into sewer collection systems (Berggren et al., 2007; Singh and Tiwari, 2019).

It is therefore important to take into consideration all the factors mentioned above (population growth, urbanization, industrialization, climate change, migration) when reviewing which emerging wastewater treatment technology/innovation to consider, especially in the case of a country like South Africa. Below are some of the emerging wastewater treatment technologies that can be employed in South Africa (Armah et al., 2021).

I. Membrane Technology

Membrane Technology as a method of wastewater treatment encompasses related engineering and scientific approaches for transporting components, species or substances through the membranes, thus removing the said species from the wastewater stream (Diez and Rosal, 2020; Armah et al., 2021). Chemical or biological wastewater treatment uses membranes for size-based separation of substances, or as standalone systems for secondary wastewater treatment (Armah et al., 2021; Diez and Rosal, 2020). Application of membrane technology has both industrial and environmental advantages such as (1) clean technology, (2) ability to replace conventional wastewater treatment processes (3) energy saving compared to conventional wastewater treatment systems like an activated sludge, (4) ability to produce good quality effluent, (5) its flexibility in system design. In a South African case, the most applicable membrane technology processes that can be introduced in wastewater treatment are microfiltration and ultrafiltration. These membrane technologies can be

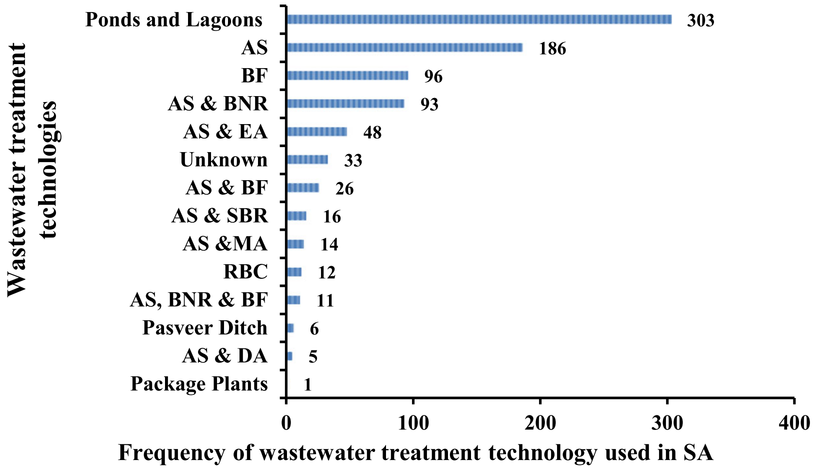

Fig. 3. Wastewater treatment technologies applied in South Africa; AS: Activated Sludge; AD: Anaerobic digester; BNR: Biological Nutrient Reactor; B: Biofilter; RBC: Rotating Biological Contractor; MA: Mechanical Aeration; SBR: Sequence Batch Reactor; EA: Extended Aeration; DA (Diffused Air)

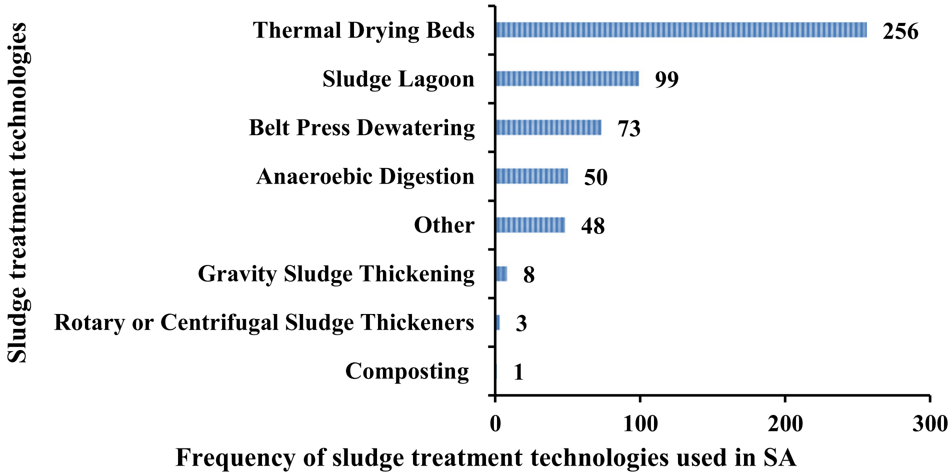

Fig. 4. Sludge treatment technologies applied in South Africa

Fig. 5. Activated sludge wastewater treatment plant in South Africa (picture taken by the author)

applied as a secondary or tertiary process of conventional wastewater treatment technologies such as activated sludge or trickling filters. Application of such membrane technology to existing wastewater treatment infrastructure to improve effluent quality would best fit where there are emerging industrial developments in areas where its effluent strength was not previously catered for in the existing infrastructure. This application can be feasible and beneficial in a South African context since existing wastewater treatment infrastructure can be modified to treat effluents of higher strength and is also cost effective.

II. Membrane Bioreactor Technology

Another emerging wastewater treatment technology that can be applied in South Africa is membrane bioreactor technology. The difference between this technological application and the membrane technology is that instead of the traditional membranes being integrated within the treatment process as a secondary or tertiary process in an existing infrastructure, ultrafiltration[1] and microfiltration[2] membranes are integrated within the bioreactor of a conventional activated sludge treatment process (Diez and Rosal, 2020). Advantages of Membrane Bioreactors include high biomass concentrations, less space requirement compared to traditional systems, lower hydraulic retention time, high effluent quality lower biosolids and higher volumetric loading (Shon et al., 2011; Rahimi et al., 2020).

This technology would be very applicable in South Africa since it requires a smaller amount of land area compared to other conventional treatment technologies, as rapid population growth, coupled with urbanization, leading to a shortage of available area suitable for the construction of new wastewater treatment systems to accommodate development. Membrane bioreactors would also be applicable for a South African context since it would be cheaper to construct and operate such treatment technology and accommodate both domestic and relatively moderate industrial effluent (Rahman et al., 2023).

Rahman et al., (2023) note, however, that even though there are several advantages to implementing membrane bioreactors for wastewater treatment over conventional treatment technologies, there are drawbacks, which include constant membrane fouling, which can be mitigated by the development of low cost and efficient membrane material and the modification of membrane surfaces based on anticipated quality and characteristics of the influent to be treated.

[1] Ultrafiltration (UF)
[2] Microfiltration (MF)

3.4. Implications towards current policies relating to wastewater treatment, sanitary development and financing

The current state of South Africa's water treatment and sanitary infrastructure, coupled with the status relating to the financing of such infrastructure, highlights the inadequacy of policy implementation and monitoring to achieve efficiency and sustainability. A study undertaken by Edokpayi et al., (2020) elucidates that the South African government has, for the past couple of years, been developing and improving the country's legislative frameworks and policies relating to wastewater treatment and sanitation development and governance. For example, in 2016, a National Sanitation Policy was developed by the DWS which establishes and guides the advancements needed in the sanitation sector, following the approval of the white paper on water supply and sanitation approved in 1994, and white paper on National Water Policy of South Africa approved in 1997. The policy aimed at providing comprehensive policy positions which address gaps and challenges within the sanitation sector, and addressed the country's new national and international developmental imperatives.

Moreover, in 2019, the South African government embarked on a process of developing a National Water and Sanitation Master Plan divided into three volumes, i.e., volume 1, highlighting key challenges and key actions required for their resolutions relating to water and sanitation infrastructure development in South Africa; volume 2, dealing with plans to action protocol; and volume 3, dealing with the schedule relating to the established actions.

It can, therefore, be established that the country's policies and legislative frameworks relating to wastewater treatment and sanitary infrastructure development are appropriate, adequate and up-to-date. However, the observed problem is the implementation and monitoring of the policies. This is in line with the study undertaken by Ajulor, (2018), which is aimed at examining the challenges relating to policy implementation in Africa and sustainable development goals. The study revealed most African countries, including South Africa, encounter challenges with regard to implementing the national policies promulgated, and monitoring their implementation, mainly due to maladministration, corruption, political dislocations, and inept leadership, leading to underdevelopment and impacting the overall national well-being.

If the main challenge towards lack of proper development relating to wastewater treatment and sanitary infrastructure in South Africa is noted as the failure of policy implementation and monitoring, then it is of utmost importance that national policies relating to monitoring and evaluation be revised, reconfigured and improved.

A study undertaken by Mello (2018) highlighted that the Auditor General of South Africa, (2016) reported poor performance of South Africa's local government (municipalities) during the financial years 2012-2013, 2013-2014 and 2014-2015, which is attributed mainly to weakness in monitoring, evaluation, and accountability systems. Effective monitoring, evaluation and accountability systems and policies enable government departments to fulfil their constitutional and legal obligations effectively, utilizing the resources efficiently. Mello (2018) further outlines that lack of capacity and poor oversight within and outside the municipalities and government institutions is one of the underlying reasons for poor performance, thus resulting in poor implementation of related policies.

In addition to improving and restructuring national policies relating to monitoring, evaluation, and accountability, it is important that relevant stakeholders such as government, private sector and communities are fully involved and harmonized for the country's developmental policy implementation to be executed and monitored effectively. Local communities and the private sector can participate in the monitoring, evaluation and accountability of an ongoing developmental project by firstly being part of the planning process through providing inputs towards integrated development plans of their municipalities, attending scheduled progress reporting meetings, engaging effectively with government institutions regarding ongoing developments through media platforms, and radio discussions. Government institutions mandated with development should also establish strategies promoting increased stakeholder engagement in planning, implementation, monitoring and evaluation process, thereby creating an enabling environment for meaningful feedback and accountability to affected and interested parties (Sulemana et al., 2018).

4. Conclusion

The integrity of South Africa's wastewater treatment and sanitary infrastructure is crucial for protecting the country's water resources, environment, and public health. While the current government has allocated significant funds to develop and upgrade this infrastructure to address past deficiencies, there are still issues in how these funds are utilized. Inefficiencies in spending have led to inadequate development and maintenance.

The study offers insights into the current state and technological advancements of South Africa's wastewater treatment and sanitary infrastructure. It reveals that the infrastructure and applied treatment technologies are generally insufficient or only partially effective in producing compliant effluent and sludge according to Green Drop standards. The study identifies several reasons for the poor state of infrastructure, despite significant capital investment, including:

1. Poor Performance of Appointed Contractors: Contractors often fail to meet the required standards.
2. Inadequate Planning: Projects lack thorough and effective planning.
3. Fruitless and Wasteful Expenditure: Funds are not always spent wisely, leading to unnecessary costs.
4. Cost Overruns: Projects often exceed their budgeted costs.
5. Lack of Project Management: There is insufficient oversight and management of projects.
6. Insufficient Operations and Maintenance: Completed projects lack adequate upkeep, resulting in dysfunctional assets.
7. Lack of Long-term Sustainability of Capital Programs: Investments do not always lead to sustainable improvements in the infrastructure.

These issues highlight the need for better management, planning, and oversight to ensure the effective use of funds and the long-term sustainability of South Africa's wastewater treatment and sanitary infrastructure.

5. Recommendations

To improve South Africa's wastewater treatment and sanitation infrastructure, it is recommended that the regulatory auditing and assessment of wastewater treatment facilities under the Green Drop Certification program should be conducted simultaneously with the annual Auditor General Local Government Audits for all municipal entities. This will allow for a comparison of the Green Drop performance with the governance accountability ecosystem. Furthermore, to enhance the country's wastewater treatment and sanitary infrastructure, the government must establish robust policies and frameworks for monitoring, evaluation, and accountability. This will ensure that state investments in infrastructure development are cost-effective and efficient and hold individuals responsible for unethical and corrupt behavior. Efforts should focus on researching and investing in new wastewater treatment technologies and infrastructure that can effectively treat complex wastewater streams while prioritizing energy efficiency and meeting strict water quality standards.

6. Research gaps

Additional research studies could involve conducting feasibility and pilot studies to assess the implementation of various emerging wastewater treatment technologies, particularly those suggested in the present study, within a South African context. Factors to consider include population growth rate, desired effluent quality, and the industries that primarily produce complex effluent.

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