Seasonal influence on the nutrient removal efficiency of a SPRAS wastewater treatment plant in the Free-State Province, South Africa

S. Mofokeng[1*]; P. Oberholster[2] and L. Hill[3]

[1] *Faculty of Natural and Agricultural Science, Centre for Environmental Management, University of Free State. P O Box 339, Bloemfontein 9300, Republic of South Africa*

[2] *Faculty of Natural and Agricultural Science, Centre for Environmental Management, University of Free State. P O Box 339, Bloemfontein 9300, Republic of South Africa*

[3] *Department of Geography, Geoinformatics and Meteorology, University of Pretoria Private Bag x 20, Hatfield 0028 Republic of South Africa*

*Corresponding Author: *sellwanemofokeng@gmail.com*

Abstract

In Africa, untreated sewage discharge is one major source of water pollution that contributes to high oxygen demand and nutrient loading on the receiving water bodies, which threatens aquatic ecosystem and human health. Sludge Process Reduced Activated Sludge (SPRAS) plant could potentially address this challenge as a technology that has been found effective in the removal of nutrients from wastewater. The objective of the current study was to investigate the nutrient removal and treatment efficiency of a SPRAS treatment plant as a case study during the cold and warm seasons in the Free State Province, South Africa. The treatment effectiveness of the SPRAS plant was assessed by comparing the final effluent data to the South African General Authorization (SAGA) guidelines for discharging wastewater into water resources. Treatment efficiency was determined by comparing raw influent to the final effluent data. Ammonia was efficiently removed from wastewater in the colder seasons compared to the warmer seasons, at 97-99% and 87-89% removal efficiency range, respectively. Suspended solids, Carbon Oxygen Demand (COD), and ortho-phosphates were efficiently removed from wastewater during both warm and cold seasons, with efficiency ranges of 97-98%, 87-89%, and 67-98% respectively. *E. coli* in the final effluent was reduced to concentrations below the set SAGA limit during both warm and cold seasons. However, SPRAS was ineffective in nitrates removal during both seasons, where the final effluent concentration failed to meet the set SAGA limits. The observed nitrates removal ineffectiveness may be attributed to operating temperatures (minimum average range of 10.5 -13.5 °C) that were not optimal for the activity of the microbial communities driving the treatment process. It was evident from the analysed data that climatic conditions may influence the treatment efficiency of SPRAS technology, with treatment efficiency reduced when air temperatures were below optimal temperatures for the growth of the microbial communities.

Keywords: Wastewater discharge, Water quality guidelines, Wastewater Treatment Plant (WWTP), Sludge Process Reduction Activated Sludge (SPRAS), Activated Sludge (AS), Sludge Reduction, and Ineffective WWTP

Introduction

Developing countries are mostly affected by poor water quality with only 5% of domestic and industrial wastewater adequately treated before being returned to the environment (UN, 2018). As such, approximately 2 million deaths of children under 5 years of age are associated with waterborne diseases (WHO and UNICEF, 2015; Forstinus et al., 2016). South Africa as a developing country has water resources that are threatened by sewage pollution from malfunctioning Municipal Wastewater Treatment Plants (WWTP) (Bwapwa, 2019). Water quality issues such as salinisation and eutrophication have been attributed to poorly treated wastewater effluent from WWTP amongst other factors, with numerous river systems identified as eutrophic (Harding, 2015). Several technical challenges have affected South African wastewater treatment technology for almost two decades resulting in the consistent production of poor-quality effluent that fails to meet the recommended discharge limits standards (WRC, 2012; Vosloo et al., 2019). The most commonly used WWTPs in the country are Biological Nutrient Removal (BNR) technologies, which employ the Activated Sludge (AS) method in their raw sewage treatment processes. The three main BNR variants are (i) conventional activated sludge, (ii) trickling biofilters, and (iii) pond and lagoon systems (Vosloo et al., 2019). Apart from the BNR technologies being limited by the use of chlorine as a disinfection method and being inappropriate wastewater technologies for site conditions amongst other factors, these technologies produce excessive Waste Activated Sludge (WAS). WAS is a byproduct of the secondary biological treatment process with disposal and handling challenges that can be hazardous to aquatic life and the environment (Dhir et al., 2017).

Previous studies have found the Sludge Process Reduced Activated Sludge (SPRAS) technology (a biologically modified activated sludge process) to be effective in reducing the production of WAS by over 70% (Zhou et al., 2014a; Zhou et al., 2014b; Jiang et al., 2018). Additionally, SPRAS is also effective in the removal of secondary nutrients and other pollutants from wastewater (Apollo, 2018). SPRAS WWTP follows a conventional (removal of large particles inclusive of debris, grit, and sand) process flow in the first stages. The influent from the primary stage, together with the recycled WAS produced in the subsequent activated sludge process is pumped into the aeration tank (Zhou et al., 2014a; Apollo, 2018). Subsequent homogenization of the influent and the WAS in the aeration tank, integrated biological treatment, sludge settling, and reduction by degradation take place in the SPRAS unit (Apollo, 2018). The mechanism of sludge reduction in SPRAS technology is hydrolysis acidification which involves hydrolytic and acidogenic bacteria (Apollo, 2018). During this process, the hydrolysis of the bacterial cell walls occurs, breaking down large molecular cell materials into smaller fermentable organic materials. These organic materials are then recycled into the aeration tank to increase heterotrophic biomass (Rodriguez-Perez and Fermoso, 2016; Apollo, 2018). The recycled organic material is known as Recycled Activated Sludge (RAS). The advantage of recycling RAS lies in its contribution to the improvement of the diversity of the microbial population, which influences the efficiency of the nitrification and denitrification processes by contributing to the overall improvement of the removal of nitrates and ammonia (Zhou et al., 2015; Apollo, 2018). Studies have reported operating parameters such as Sludge Retention Time (SRT), process temperature, and Dissolved Oxygen (DO) to have an impact on the efficiency of nutrient removal in activated sludge plants (Shahzad et al., 2015; Awolusi et al., 2016). Lower process temperatures were reported to result in the reduction efficiency of ammonia removal from wastewater (Zhou et al., 2014a). Additionally, Niu et al. (2016) attributed the decrease in microbial diversity which negatively affects the sludge reduction to high DO concentration. The final stage of the SPRAS unit treatment involves disinfecting the treated wastewater using Ultra-Violet (UV) light in the UV lamp chamber before discharging the treated wastewater (Apollo, 2018). Although UV radiation as a disinfection method is associated with reduced negative impacts on human and environmental health, its effectiveness is affected by operating and water parameters including the UV intensity of the lamps used, reactor residence time, and wastewater turbidity levels (Collivignarelli et al., 2017). Moreover, microorganisms have been reported to undergo natural processes such as bioflocculation and photoreactivation (Kollu and Örmeci, 2012; Shafaei et al., 2016). Photoreactivation is a process in which microorganisms repair the damage to their DNA or RNA after exposure to UV radiation of visible wavelength (310 - 480 nm) (Kollu and Örmeci, 2015). In bioflocculation microorganisms form flocs with each other or other organic and inorganic particles without the aid of any chemicals (Kollu and Örmeci, 2012). Bioflocculation result in shielding and embedding of the target organism resulting in UV light losses thus reducing the effectiveness of the method (Kollu and Örmeci, 2012). Bioflocculation has also been reported to reduce the reliability of traditional plate count methods used in determining the concentration of pathogens in treated effluent (Manickum, 2020).

The SPRAS technology has been found to substantially remove nutrients from raw wastewater in several pilot and full-scale WWTPs in China (Zhou et al., 2014a; Zhou et al., 2014b; Jiang et al., 2018). In a study conducted in Shanghai, a modified SPRAS technology was compared to the conventional anaerobic/anoxic/aerobic (AAO) process, over a period of 217 days which was divided into four phases. The study found that the SPRAS system achieved a final pH value of 5.9 at the end of phase 2, and a suspended solids removal efficiency of 82.9% compared to the 71.8% of the AAO process. The final average COD removal efficiency was 91.2% at the end of the four-phased process compared to the 85.5% at the end of phase 1. The increase in the COD removal efficiency was attributed to the increase in temperatures (Zhou et al., 2014a).

All biological nutrient removal processes are carried out by microbial activity which is highly influenced by temperature (Awolusi et al., 2016). Therefore, the climate of the area where the WWTP is located plays a significant role in the effectiveness of nutrient removal from wastewater. SPRAS technology has the following advantages over the current BNR technologies in use in South Africa: (i) production of reduced WAS while effectively removing pollutants to acceptable discharge standards and (ii) disinfection by UV light technology, avoiding all challenges associated with chlorine disinfection. However, the use of SPRAS technology in South Africa is not widespread, and little is known about the technology's performance under South African climatic conditions. Hence, the objectives of this study were to: (i) Assess the effectiveness of the installed SPRAS packaged plant in the Free State Province of South Africa in reducing parameters namely: pH, Electrical Conductivity, COD, Ammonia, Nitrates, Suspended Solids, Faecal coliforms and *E.coli* to recommended standards (as per wastewater discharge limits set out in the National Water Act, Government Gazette No. 20526, 8 October 1999), over 2 years after installation; (ii) assess the influence of temperature on treatment effectiveness (i.e. pH, Electrical Conductivity, COD, Ammonia, Nitrates, Suspended Solids, Faecal coliforms and *E.coli*) of the installed SPRAS packaged plant in the Free State Province of South Africa and (iii) to identify barriers and the feasibility to the widespread adoption of the SPRAS technology across African countries.

Materials and Methods

Case Study area and background

The climate type of the Free-State province is mostly a C (temperate) climate type, with the SPRAS treatment plant (treatment capacity of 450 m3/day) located at Glen village (28°56'35.1" S 26°19'29.7"E) near the city of Bloemfontein (Figure. 1) within the BSk (cold semi-arid) climate type classification (Peel et al., 2007; Conradie and Kumirai, 2010). The SPRAS treatment plant treats domestic wastewater and wastewater from a range of agricultural activities including a piggery, dairy, and an abattoir.

The WWTP services a total of 2000 people including village residents, college students, members of the police force, and the Free-State Department of Agriculture and Rural Development (FSDARD) officials. The plant, one of the three pilot plants installed in South Africa by OPECS, discharges its treated effluent into the Modder River. The plant is registered and classified as Grade 1, according to regulation 2834 (Government Gazette, 2013). Grade 1 WWTPs serve 2000 people or less with a collection system serving up to 2500 people.

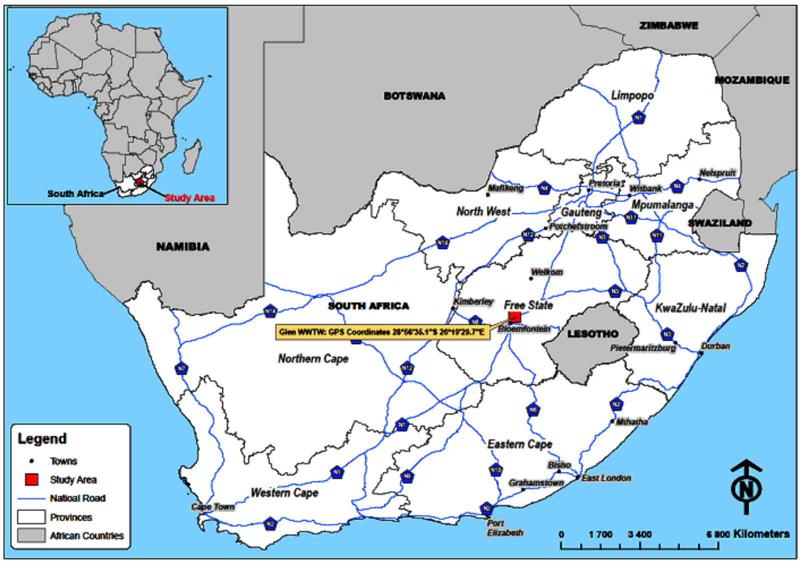

Fig. 1 Map of the study area

Physical, chemical, and microbial sampling

The nutrient removal effectiveness of the SPRAS WWTP was assessed by analyzing the raw influent and final effluent. Standard sampling protocols were followed by FSDARD to generate the data used in the current study: Samples for chemical analyses were collected using glass bottles, which were rinsed three times before being filled. The glass sample bottles were marked with the location (site name), sampler's name, date, and time of collection using a permanent marker. The cap of the bottle was not removed until the sample was ready to be taken. The microbial samples were collected in 500 ml microbial bottles that were sterilized, and ample air space was left in the sample bottle to allow sample mixing. Both chemical and microbial water quality samples were stored and transported in cooler boxes with ice packs. The samples were delivered to a South African National Accreditation System (SANAS) accredited laboratory for analysis within 12 hours after collection.

The following water quality parameters were analysed in the raw influent and final effluent: pH, Electrical Conductivity (EC), Ammonia, Nitrates, Phosphates, Chemical Oxygen Demand, Suspended Solids, Faecal Coliforms, and Escherichia coli. All the water samples collected were subject to standard chemical analysis procedures detailed in "Standard Methods for the Analysis of Water and Wastewater" (APHA, 2017). Methods used for each analyte are shown in Table 1.

TABLE 1

Standard methods used for analytes in the study

Analyte	**Method**
pH	TM/pH/05
Electrical Conductivity	TM/EC/06
Ammonia	HACH 8038
Nitrates	HACH 8039/8171
Phosphates	HACH 8178
COD	HACH 8000
Suspended solids	TM/TSS/04
Faecal Coliforms	QM no: 5.4/TM-01
Escherichia coli	QM no: 5.4/TM-02

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[1](Source: Adapted from APHA, 2017)

The data received were analysed as follows: to assess the nutrient removal effectiveness of SPRAS, the final effluent data was compared to the general limits of the South African General Authorization (SAGA) guidelines in terms of Section 39 of the National Water Act, 1998 (ACT NO. 36 of 1998) for discharging wastewater into water resources. The raw influent data was compared to the final effluent data to determine the treatment efficiency of the installed SPRAS plant. According to the SAGA legislation, general limits are used for WWTPs that discharge effluent up to 2000 cubic meters on any other day into a non-listed water resource (as set out in the guideline), and special limits apply to WWTPs discharging up to 2000 cubic meters into listed water resources (SADWS, 2013). *E. coli* is not set as a limit in the SAGA, in this study the general limit for faecal coliforms will be used for the assessment of the removal effectiveness of SPRAS, see Table 2 for the general and special limits.

Available data were collected between November 2017 and January 2019. There was a general lack of consistency in monitoring and data collection during this selected study period due to financial reasons. In 2017 data was collected in November and December, for 2018 in April, May, September, October, and November, and finally in January 2019. The attempt to analyze the data in the rainy and dry seasons failed as there was not enough data available for the dry season months. Therefore, for the available data two seasons, namely summer and winter were analysed. Data for spring and summer which represent warm/summer seasons were selected from November and December 2017, September to November 2018 and January 2019. April and May 2018 represented the cold/winter season. Additionally, the data available was inadequate to make any statistical analyses possible. The graphical representation of the data sets (raw influent and final effluent) as single values are presented as basic bar graphs, plotted in Microsoft Excel. The bar graphs are used to compare the water quality parameters for the final treated effluent for the available data over the two studied seasons with the set target SAGA discharge standards.

Results

Temperature

Air temperature data for the city of Bloemfontein, located 26 km away from Glen village was used for this study period (Table 3).

Nutrient removal effectiveness and treatment efficiency: Warm Season

The warm seasons had a minimum air temperature range of 9-18 °C and a maximum range of 24 -32°C. During this season, October 2018 with the minimum and maximum air temperatures of 13°C and 27°C was the

TABLE 2

South African General Authorization general and special limits for effluent discharge into water resources

Determinant	Unit	General Limit	Special Limit
Faecal Coliforms	MPN/100ml	1000	0
Chemical Oxygen Demand	mg/l	75	30
pH	pH units	5.5-9.5	5.5-7.5
Ammonia as Nitrogen	mg/l	3	2
Nitrate/Nitrite as Nitrogen	mg/l	15	1.5
Electrical Conductivity	mS/m	(70 m/S/m above intake to a max 150m/S/m)	(50 m/S/m above background receiving water to a maximum of max 100 m/S/m)
Orthophosphate as Phosphorous	mg/l	10	1(med.) 2.5 (max)
Suspended solids	mg/l	25	10

[2]

[2](Source: adapted from SADWS,2013)

TABLE 3
Maximum and minimum air temperatures for Bloemfontein for the period November 2017 to January 2019

Month	Minimum Temp. (°C)	Maximum Temp. (°C)	Mean Temp. (°C)
Warm Season			
November 2017	14	28	25
December 2017	17	30	27
September 2018	9	24	19
October 2018	13	27	23
November 2018	14	30	25
January 2019	18	32	28
Cold Season			
April 2018	13	24	20
May 2018	8	21	16

[3]

[3](Source: Adapted from SAWS, 2018; SAWS, 2019; SAWS 2020)

month where the SPRAS WWTP was mostly ineffective in nutrient removal efficiency. As shown in Figure. 2, the SPRAS plant was ineffective in removing ammonia (NH_4), with the concentration of the final effluent above the SAGA limit of 3 mg/l for half of the season.

Apart from NH_4, the SPRAS plant was ineffective in the treatment of COD, suspended solids, *E. coli*, and faecal coliforms in October 2018, with the values of the final effluent being above the recommended SAGA limits. Although the nitrates concentration remained below the SAGA limit (Figure. 3), the final effluent had a higher concentration of nitrates than the influent, except for October 2018.

The pH levels for this season remained within

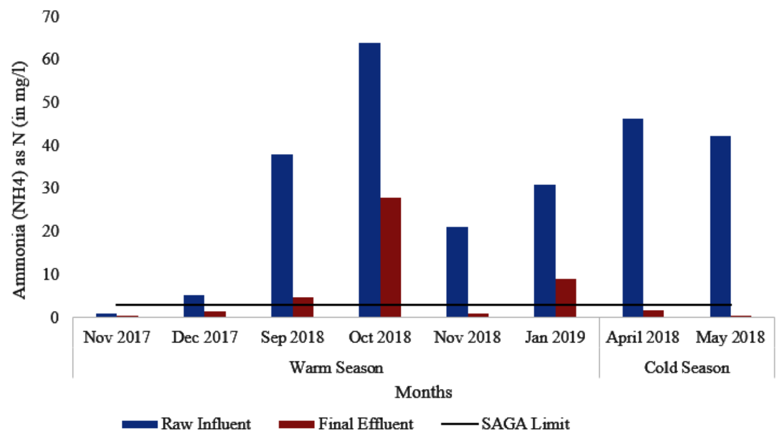

Fig. 2 Differences in ammonia concentration load

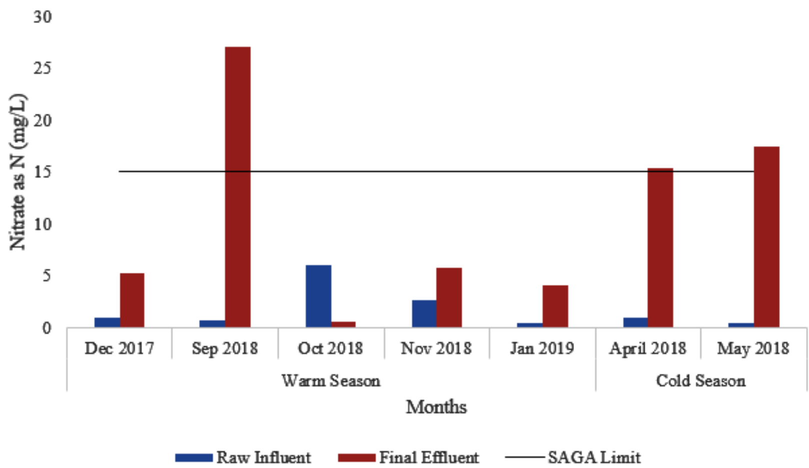

Fig. 3 Differences in nitrates concentration load

the SAGA limit range of 5.5 to 9.5 pH units. However, for two months of the season December 2017 (minimum and maximum air temperatures 17°C and 30°C respectively) and April 2018 (minimum and maximum air temperatures 13°C and 20°C respectively) the final effluent had a higher pH than the raw influent, even though it was below the upper SAGA limit (Figure. 4). The same observation was made for October 2018. The overall average pH reduction was 0.34 pH units, with an average treatment efficiency of 3.6% over the season.

Although the EC in the influent was below the SAGA recommended limit of 150 mS/m, the SPRAS plant still effectively reduced the EC in raw influent by an average treatment efficiency of 10.69 % in the warm seasons (Figure. 5). The exception was in October 2018, where the final effluent had higher concentration than the influent.

The highest ortho-phosphates load in the final effluent was observed during October 2018 and April 2018, where the SAGA limit of 10 mg/l was exceeded by 11 mg/l for both months (Figure.6).

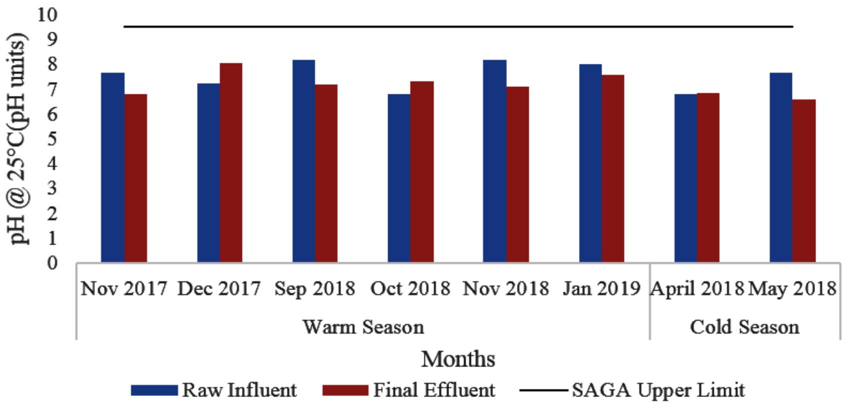

Fig. 4 Differences in pH

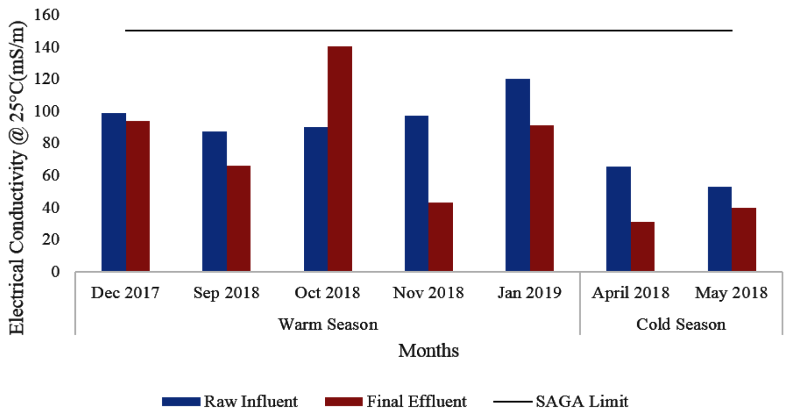

Fig. 5 Differences in EC

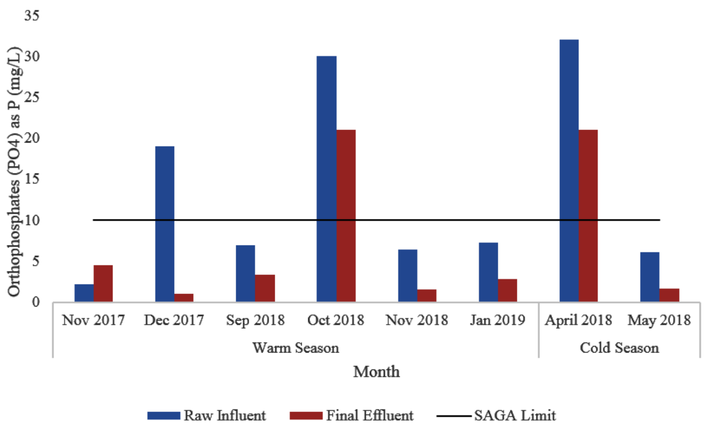

Fig. 6 Differences in ortho-phosphates concentration load

The average treatment efficiency between raw influent and final effluent in the removal of COD (Figure. 7), ortho-phosphates, suspended solids (Figure. 8), *E. coli*, and faecal coliforms (Table 4) was 68%, 34%,75%, 71.5%, and 43% respectively. COD and suspended solids in the final effluent also remained below the SAGA limit of 75 mg/l and 25 mg/l except for October 2018 (as shown in Figure. 7 and Figure. 8). Furthermore, *E. coli* and faecal coliforms in the final effluent remained below the SAGA limit of 1000 count/100ml throughout the study period, except in September 2018 when the minimum and maximum air temperatures were 9 and 24 °C.

Nutrient removal effectiveness and treatment efficiency: Cold Season

The cold season was represented by data collected for April (minimum and maximum air temperatures were 13 and 24 °C respectively) and May (minimum and maximum air temperatures were 13 and 24 °C respectively) 2018. Data for *E. coli* and faecal coliforms (Table 4) were only available for April 2018. The treatment efficiencies were 99.8% and 99.9% with the final effluent below the SAGA limit of 1000 MPN/100mL. The SPRAS technology failed to remove nitrates in accordance with SAGA limits, where the final effluent concentration was higher than that of the influent and the SAGA limit of 15 mg/l for the whole season (Figure. 3). During this time minimum and maximum air temperature ranges were 8-13°C and 21 -24°C.

The overall average pH reduction was 0.83 pH units, producing final effluent within the SAGA limit range of 5.5 – 9.5 pH units for the season (Figure. 4), with an average treatment efficiency of 6.5%. EC reduction

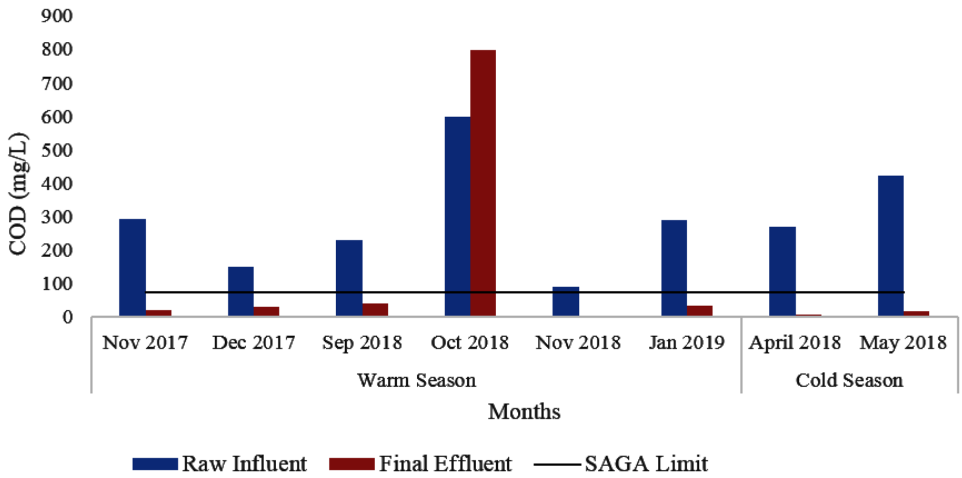

Fig. 7 Differences in COD concentration load

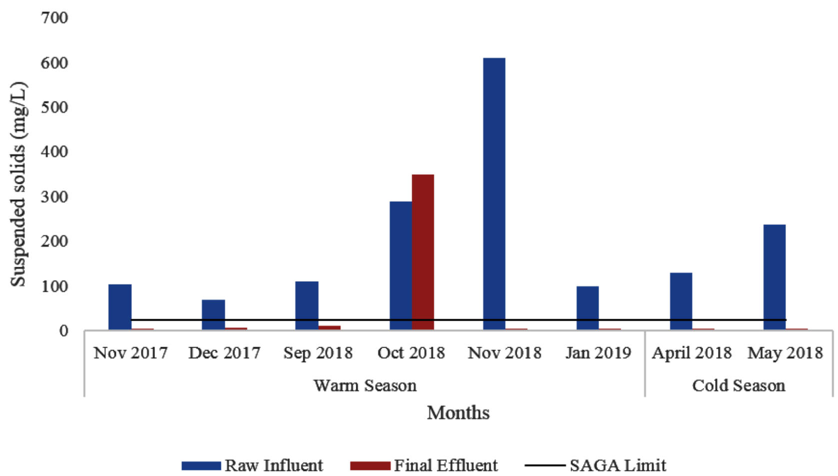

Fig. 8 Differences in suspended solids concentration load

TABLE 4
Differences in *E. coli* and faecal coliforms concentration load

	***E. coli* (MPN/100mL)**		**Faecal Coliforms (MPN/100mL)**	
SAGA Limit	1000 MPN/100 mL			
Warm Season				
Months	Raw Influent	Final Effluent	Raw Influent	Final Effluent
Nov 2017	2420	411	-	-
Dec 2017	2420	110	2420	2420
Sep 2018	3500	2300	8200	7700
Oct 2018	620	510	990	890
Nov 2018	7000	1	15000	1
Jan 2019	24000	1	72000	1
Cold Season				
May 2018	2420	4	2420	2

was in the range of 10-34 mS/m (Figure. 5), with an average treatment efficiency of 39% over the season. The average treatment efficiency between raw influent and final effluent of ammonia, ortho-phosphates, COD, and suspended solids were 98%, 95%, 98%, and 66% respectively (Figure. 2; Figure. 6 - 8). Except for ortho-phosphates for April 2018 when the min air temperature was 13°C and max 24°C, the final effluent contained concentrations lower than the discharge limits of 10 mg/l, 75 mg/l, 25 mg/l, and 3 mg/l for orthophosphate, cod, suspended solids and ammonia respectively.

Discussions

The observed treatment efficiency trend of the SPRAS plant in the current study was higher treatment efficiency during the cold season than in warmer seasons. This trend was observed for all parameters except for nitrites. The reduced treatment efficiencies during the warmer seasons may be attributed mainly to the fact that the warmer seasons coincide with the rainfall season in the Free-State province of South Africa. Thus, during warmer seasons the plant receives higher volumes of influent from the agricultural college farm, stormwater, and other non-domestic wastewater sources from the upstream agricultural land use activities, with increased pollutants and pathogens load. The result is the reduced residence time of wastewater in the treatment tank, resulting in reduced treatment efficiency.

October 2018 corresponds to the time when the plant started experiencing regular tripping due to faults along the electricity supply line caused by overdue service of the substation it feeds from. Additionally, the maintenance team reported voltage surges at the plant also resulting in the random tripping of the main switch, with the consequent ceasing of operations. Other results of the high voltages were the burning up of pumps, UV lamps, and electrical cables thus the plant failed to treat most pollutants in October 2018. The observation during November (orthophosphates) and December (pH) 2017, where the final effluent concentration was higher than the influent can be attributed to the acclimatization of the plant since the installation works were recently completed, and operations had just resumed.

The SPRAS plant failed to treat nitrates for the study period, the credible cause of the increased concentration in the final effluent than the influent is the high concentration of nitrates in the produced sludge which the hydrolytic and acidogenic bacteria were unable to effectively reduce, hence the increased concentrations in the final effluent. Additionally, the organic matter may have also contained a high concentration of nitrogen, and was not being effectively recycled, thus the plant may not have been functioning effectively. Several studies have given attributable factors to the ineffectiveness, diversity and concentration of the bacteria involved in sludge reduction and pollutants removal in activated sludge plants (Batstone et al., 2002; Rodriguez-Caballero, 2012; Ai et al., 2019; Alisawi, 2020). The major factor causing the ineffectiveness of acidogenic and hydrolytic bacteria is wastewater temperature (Ai et al., 2019; Alisawi, 2020). Ai et al. (2019) reported an increase in the total nitrogen concentration in the final effluent with a temperature decrease from 20 to 5 °C while the operating temperature range for mesophilic microbes such as acidogenic and hydrolytic bacteria was reported at 10 - 45°C with the optimum at 32.5°C (Batstone et al., 2002). Additionally, Kruglova et al. (2017) attributed decreased growth rate of nitrifying bacteria biomass to lower temperatures. The mean air temperatures for the current study period ranged from 16 to 28 °C, this implies an even lower wastewater temperature range for the SPRAS plant, thus the operating wastewater temperatures were not optimal for the functioning of the acidogenic and hydrolytic bacteria.

The effectiveness of the SPRAS plant in the current study in reducing the final pH in the effluent in both cold and warm seasons to below the recommended SAGA upper limit of 9 pH units was consistent with the findings from the study conducted at a conventional AS plant in the North-West province of South Africa that employs the trickling filter technology in treating domestic and agricultural wastewater. The AS plant had a treatment capacity of 45,000 m^3/day (Makuwa et al., 2020). The conventional AS plant attained a final effluent concentration in the range 7.03-8.49 pH units. Similar observations were made for EC, the SPRAS in the current study produced effluent that remained below the SAGA limit of 150 mS/m, which was consistent with the conventional AS plant (Makuwa et al., 2020) which achieved a final effluent concentration range of 30.9 -140 mS/m. The observed COD removal effectiveness of the current study SPRAS plant was comparable to that of Zhou et al. (2014b) which compared pilot scales anoxic/aerobic (AO) plant with the SPRAS plant. The WWTPs in the latter study were both fed 50L/day of wastewater from Dongqu WWTP in Shanghai China (Zhou et al., 2014b). The SPRAS plant by Zhou et al. (2014b) achieved an average COD reduction efficiency of 86.6%, while the current study SPRAS overall average efficiency was 80.4%. The SPRAS plant's overall average *E. coli* removal efficiency was lower in comparison to the conventional AS plant studied by Makuwa et al. (2020) which achieved an overall *E. coli* removal efficiency of 99.77%. The warm season's removal efficiency range was 99.09-99.98% while the cold season's efficiency range was 99.65-99.86% for the conventional AS plant. Except for September 2018 in the case of the SPRAS plant, both plants can be considered effective, as the final effluent discharged had *E. coli* concentrations less than the SAGA limit of 1000 MPN/100ml. Apart from increased influent volumes and pathogen load due to the rainfall during the warmer seasons, the other reported factor influencing the effectiveness of UV disinfection is high turbidity levels (TSS > 30 mg/L) where low-intensity UV lamps (< 9 mJ/cm2) are used (Garay et al., 2022). However, for the SPRAS plant of the current study, the final effluent had suspended solids concentrations below 10 mg/L throughout the study period, except for October 2018. Hence, the synergistic influence of turbidity on *E. coli* deactivation can be ruled out for the current study SPRAS plant. Other attributable factors to the observed lower efficiency during warmer seasons than colder one includes the photoreactivation abilities of *E. coli* under low intensity (< 9 mJ/cm^2) UV radiation (Kollu and Örmeci, 2015), and bioflocculation which results in shielding and embedding of the target organism inhibiting UV light exposure (Kollu and Örmeci, 2012). The overall average treatment efficiency of faecal coliform removal was lower compared to the treatment efficiencies achieved by a conventional activated sludge WWTP studied by Miranzadeh et al. (2013), with an overall average treatment efficiency of 94.2%, winter treatment efficiency range of 74.5% to 83%, and a summer removal efficiency greatest at 92.9%. The SPRAS plant in the current study however can be considered more effective in the removal of the faecal coliforms than the conventional AS in the study by Miranzadeh et al. (2013), since the final effluent of the AS system had higher counts of faecal coliforms ranging from 5200 to 230 000 count/100ml. These values were higher compared to the two limits namely, (i) the Iranian permissible limit for unrestricted irrigation of 400 count/100ml and (ii) the WHO of 1000 count/100ml for unrestricted irrigation used in that study. The SPRAS plant managed to produce a final effluent with faecal coliforms below the SAGA limit of 1000 counts/100ml for 66% of the study period.

The final effluent concentrations of suspended solids for both seasons remained below the SAGA limit of 25 mg/l in the current study. These observations are comparable with the results obtained by (Jiang et al., 2018) where the suspended solids concentration of the final effluent from a full-scale SPRAS plant situated in Shanghai, China was below the 35 mg/l limits of the European Union (EU) directive 91/271/EEC and 10 mg/l for Grade 1A discharge limit GB18918-2002 of China after 180 days.

The observations for ammonia removal efficiency of SPRAS technology in the current study were contrary to the findings from a study conducted in Shanghai China, where there was an increase in the final effluent concentration of NH_4 from 6 to 15 mg/l as the wastewater temperatures dropped from 12 to 7°C (Zhou et al., 2014a). In the latter study, the SPRAS was compared to the AOO system. The two pilot plants were fed with activated sludge from Bailonggang WWTP in Shanghai China and operated for 217 days (Zhou et al., 2014a). Lower temperatures have been reported to inhibit the efficiency of nitrifying bacteria during the cold season (Awolusi et al., 2016). However, in the current study, the SPRAS plant's greatest ammonia removal efficiency was achieved in the cold season when the mean air temperature range was 16-20°C, implying even lower wastewater temperatures. Additionally, the final effluent had concentrations below the SAGA limit of 3 mg/l for all months of the cold season, deeming the technology effective in the removal of ammonia for the cold season. Hence, operating temperatures can be ruled out as a possible cause for the observations made. Apart from the increased influent volumes during warmer seasons, process parameters that could have influenced the observed ineffectiveness include Sludge Retention Time (SRT), Carbon to Nitrogen (C: N) ratio, and DO (Awolusi et al., 2016). These parameters were not investigated in the current study.

The technology of the current study was also more efficient in removing ortho-phosphates during the cold season than during the warm seasons, these findings contrast with the finding of Makuwa et al. (2020) where the highest cold season treatment efficiency was 93.24% and that of the warm season was 96.99%. The average overall removal efficiency over the cold and warm seasons was 91.46% for the latter. The mean air temperatures for the warm season were in the range of 19-28°C for the current study, which is below optimum temperatures for hydrolysis acidification to produce Volatile Fatty Acids (VFAs) which are central in the removal of phosphorus. The reported optimum temperature for hydrolysis acidification, according to the study by Yang et al. (2014) is 35 °C for organic waste. Hence the observed differences between warmer and cold seasons treatment efficiencies may be attributed to operating temperatures that were below optimum operating temperature.

Barriers and feasibility for widespread adoption of the SPRAS technology in African countries

The optimum temperatures for nitrifying biomass were reported to be in the range of 25 - 28°C, where a decrease in liquid temperature to 10°C resulted in a large decrease in the specific activity of the ammonium oxidizing bacteria (Paredes et al., 2007). The reported optimum temperature to produce VFAs which are central in the removal of phosphorus in hydrolysis acidification was 35 °C for organic waste (Yang et al., 2014). Additionally, the optimum temperature for mesophilic microbes such as acidogenic and hydrolytic bacteria, responsible for sludge reduction in the SPRAS technology was reported to be 32.5°C (Batstone et al., 2002). The maximum average air temperatures for the warmer seasons and cold seasons were 28°C and 16°C respectively for the South African case study. The implications are lower than optimal wastewater temperatures for the thriving of microbial communities driving sludge reduction and nutrient removal processes in the SPRAS technology.

Apart from the temperature and operating parameters of the SPRAS WWTP, technical and maintenance issues played a significant role in its failure to treat some of the pollutants effectively. For example, since the plant was commissioned, the mechanical coarse screen in the head works had not been functioning. This resulted in foreign objects blocking the macerator slurry pumps in the pump chamber and the buffer tank. Thus, the pumps, buffer tank, and pump chamber required regular cleaning up to avoid blockages and discharge of untreated wastewater. Additionally, since this was a new technology in the country spare parts were not readily available. The mechanical coarse screen in the inlet works which broke down was manufactured in Germany and took 3 months before it could be shipped to South Africa. Other parts such as the UV disinfecting bulbs which need to be replaced regularly are a challenge to source locally. Moreover, site-specific conditions such as electricity capacity and supply were not thoroughly factored into the pre-feasibility study, although this was resolved by installing a voltage regulator treatment effectiveness was negatively affected during certain months.

Conclusions

The outcome of this study showed that temperature and precipitation were the probable cause of the ineffectiveness of the SPRAS technology to reduce nitrates to meet the SAGA limits for sewage effluents discharged into water bodies. The Cold Semi-Arid (BSk) climate zones of the case study area did not provide a conducive environment for the activity of the nitrifying bacteria, production of VFAs in hydrolysis acidification, and sludge reduction by hydrolytic and acidogenic bacteria. While the distribution of precipitation increased the influent received by SPRAS technology during warmer seasons, negatively impacting its treatment efficiency.

It is therefore recommended that for all the SPRAS installations in the arid cold and temperate African climates, the operating temperatures be increased, using supplementary heat sources to achieve the optimum operating temperatures for the nitrifying biomass and production of VFAs in hydrolysis acidification.

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