Received: 7 January 2023 | Revised: 19 April 2023 | Accepted: 22 April 2023

DOI: 10.1002/wer.10873

RESEARCH ARTICLE

water ENVIRONMENT RESEARCH

The impact of irrigation with treated wastewaters on soil and kikuyu grass nutrient compositions

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Funding information
The authors declare that no funds, grants, or other support were received for conducting this study.

Abstract

A lysimeter study was conducted for 1 year to examine how the source of wastewater for irrigation impacted soil physicochemical properties and kikuyu grass (*Pennisetum clandestinum*) nutrient composition. The wastewater used included treated wastewater produced by a membrane bioreactor (MBR) and intermittently decanted aerated lagoon (IDAL) treatment systems. No significant differences were observed between the treatments regarding total nitrogen and total phosphorus across the depths of the columns. However, highly significant differences were observed for Na content of the soils at various depths. Remarkable differences were recorded for soil exchangeable K and Na at different depths. In contrast, soil exchangeable Ca and Mg experienced no significant differences concerning the depth of the columns. For kikuyu grass, sodium contents of the grasses irrigated with MBR and IDAL treated wastewaters increased more than 200% and 100%, respectively, when compared with the grass irrigated with tap water. Over the period of monitoring considered in this study, there was no sign of excessive soil salinity/sodicity issues. The MBR treated wastewater has the potential to supply the grass with a constant dosage of valuable nutrients such as N and P without the requirement of using chemical fertilizers. This reduces the risk of contamination of receiving waters and groundwater and enhances the recycling of the nutrients in the wastewater to achieve a circular economy of nutrients.

Practitioner Points

- Application of treated wastewaters revealed no harmful effects on soil and plant nutritional properties over the study period.
- The membrane bioreactor (MBR) treated wastewater potentially supplies the grass with constant dosage of valuable nutrients in the absence of chemical fertilisers.
- Sodium contents of the grasses irrigated with MBR and IDAL treated wastewaters increased more than 200% and 100%, respectively.
- Soil soluble and exchangeable cations showed very similar trends of changes versus the depth of the soil over the study period.

KEYWORDS
intermittently decanted aerated lagoon, membrane bioreactor, nitrogen, phosphorus, Soil exchangeable cations

INTRODUCTION

Recently, the freshwater shortage is becoming widespread in both developed and developing countries due to the increasing demand for freshwater supplies. The World Economic Forum, in its recent yearly risk report, introduces water crises as the biggest worldwide hazard regarding its potential effect (Mekonnen & Hoekstra, 2016). World's increasing population, improving living standards, and the need for expansion of agricultural irrigation are the main reasons for the increasing global demand for water (Ercin & Hoekstra, 2014). The reuse of treated wastewater, nowadays, has gained noticeable attention as a proper resource contributing to efficient and sustainable water usage (Kalavrouziotis et al., 2015). Wastewater reclamation for the irrigation not only can be an effective solution for the water shortage around the world but also can reduce the pressure on the environment by decreasing the effluent discharge into receiving waters which would result in pollution reduction (Exall, 2004). A large amount of organic and inorganic nutrients such as nitrogen and phosphorus in wastewater makes it even more valuable for irrigation of agricultural lands where it can contribute to the lesser usage of commercial fertilizers.

Wastewater usage for irrigation of agricultural lands has been reported to affect the soil and plant properties in various agricultural systems (Heidarpour et al., 2007; Herpin et al., 2007; Qian & Mecham, 2005; Rai et al., 2011; Rusan et al., 2007; Tahtouh et al., 2019). Availability of mineral macro and micro nutrients for plant growth, soil pH, soil buffer capacity, and soil cation exchange capacity (CEC) can be affected as a result of wastewater application (Rusan et al., 2007). Further, wastewater usage has been reported to affect the water holding properties at different levels depending on the soil texture (Loy et al., 2018; Pinkerton et al., 2021). The main issue with high salinity of wastewater in addition to increasing sodium adsorption ratio (SAR), is the increase in soil pH. Under these circumstances the accessibility of certain plant nutrients decreases leading to severe loss in crop production (Sharma, 2006). As a result, wastewater usage for irrigation should be managed to consider the nutrient requirements of specific crop and the contents of plant nutrients in the soil, and other soil physicochemical parameters (Kiziloglu et al., 2008). However, depending on soil texture, type of wastewater, plant species, and climatic conditions, the effects of wastewater irrigation would vary on soil properties and plant production (Gwenzi & Munondo, 2008).

Depending upon the type and amount of salts, soil texture, plant type, growth stage, and environmental factors (rainfall, humidity, and temperature), the level of adverse effect of sodicity would be different. In general, soils are classified as saline, sodic or saline-sodic based on soil saturated extract EC (EC_{SE}) and SAR or the sodium on the exchange sites (i.e., exchangeable sodium percentage (ESP). Soils with EC_{SE} values more than 4 dS/m are considered as saline soils, whereas soils with similar EC_{SE} and SAR higher than 13 of the saturation extract or ESP higher than 15% are known as saline-sodic soils. Lower EC_{SE} (<4 dS/m) but SAR of more than 13 of the saturation extract or ESP more than 15% represent the soil with sodicity characteristics (Richards, 1954).

On the other hand, the nutrient uptake by plant is the function of various factors including soil ambient acidity level, soil salinity or sodicity status, composition of soil solution and exchange complex, environmental temperature, humidity, the form and concentration of different minerals and nutrients, plant species and their nutrient requirements and several environmental factors (Jewell, 2015; Qadir & Schubert, 2002).

Depending on the process of treatment, different categories of treated wastewater are produced that vary in their nutrient contents and characteristics. The membrane bioreactor treatment system (MBR), which is, nowadays, used broadly for treating municipal and industrial wastewaters, is a secondary treatment of wastewater process (STW) that combines a membrane process like microfiltration or ultrafiltration with a biological process (Judd, 2010). Another treatment process is intermittently decanted aerated lagoon treatment system (IDAL), which provides an advanced treatment of wastewater (ATW) for removing nutrients, particularly nitrogen. In IDAL system the functions of sedimentation, biological treatment, and clarification processes take place in one reactor (Ngo et al., 2007). Application of different types of wastewaters for turf grass irrigation and their influence on soil–plant system have been reported by some researchers around the globe (Candela et al., 2007; Castro et al., 2011; Gwenzi & Munondo, 2008; Kafil et al., 2019; Mclennon, Solomon, & Davison, 2020; Mclennon, Solomon, Neupane, & Davison, 2020; Parvanak & Khamisabadi, 2020; Sousa et al., 2011). Owing to the substantially different treatment methods, MBR and IDAL produce significantly different treated wastewater in terms of nutrient and salinity levels. Study of possible interactions amongst these features are of crucial importance when it comes to yield that can be obtained from a particular plant. Kikuyu grass is a C4 tropical grass widely used in sports fields, pastures, public areas, and golf course fairways (Fulkerson, 2007). Most studies on kikuyu grass have been accompanied by commercial fertilizer usage (Botha et al., 2008; Gherbin et al., 2007; Radhakrishnan et al., 2006). However, the influence of salinity present in the treated wastewater on the nutrient requirement of kikuyu grass in the absence of commercial fertilizer has not been reported in the literature, and this manuscript aims to elucidate this gap and provide more in depth information in this regard.

The specific objectives of this study were

- to investigate the effect of irrigation with treated wastewaters obtained from MBR and IDAL systems on soil physicochemical properties in comparison to tap water (TW) and
- to understand the variations in the nutrients and cation contents of kikuyu grass irrigated with different types of treated wastewaters and TW.

MATERIALS AND METHODS

Site description and experimental design

A full description of the study area and experimental design has been provided in Shahrivar et al. (2019). In brief, a column study was conducted at the Werrington South Campus of Western Sydney University during autumn 2016 till summer 2017. Three identical stainless-steel columns 450 mm in diameter and 600 mm in height were filled uniformly with the pre-prepared soil collected from Hawkesbury Campus of Western Sydney University. The schematic set-up of the columns is shown in Figure 1.

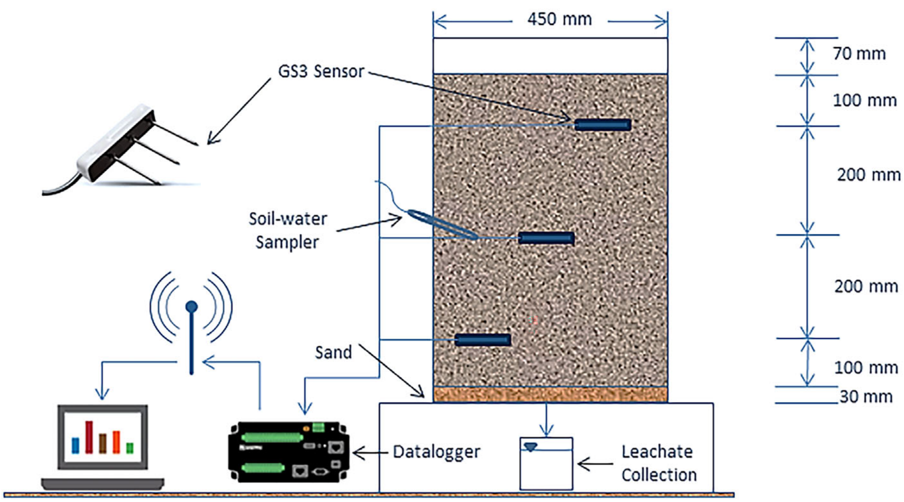

FIGURE 1 Schematic set-up of the columns.

TABLE 1 Mean values of selected parameters of initial soil and irrigation waters.

Initial soil		Irrigation waters			
Parameters	**Value**	**Parameters**	**MBR**	**IDAL**	**TW**
pH_{SE} (saturated extract)	5.9 ± 0.39	pH	7.25 ± 0.41	7.52 ± 0.35	7.25 ± 0.46
EC_{SE} (saturated extract), (dS/m)	0.55 ± 0.01	$EC_{25°C}$ (dS/m)	0.99 ± 0.18	0.93 ± 0.073	0.26 ± 0.026
Total nitrogen (TN) (g/kg)	1.11 ± 0.04	TN (mg/L)	15.33 ± 3.28	0.90 ± 0.32	0.58 ± 0.33
Total phosphorus (TP) (g/kg)	0.151 ± 0.01	TP (mg/L)	5.55 ± 2.10	1.31 ± 0.75	0.48 ± 0.44
Exchangeable ca ($cmol_C$/kg air dry soil)	1.38 ± 0.06	Ca^{2+} (mg/L)	29.59 ± 5.51	16.10 ± 1.70	20.33 ± 4.61
Exchangeable K ($cmol_C$/kg air dry soil)	0.08 ± 0.01	K^{+} (mg/L)	25.69 ± 7.28	28.58 ± 8.14	7.74 ± 5.42
Exchangeable mg ($cmol_C$/kg air dry soil)	0.48 ± 0.03	Mg^{2+} (mg/L)	11.57 ± 3.39	26.04 ± 4.62	7.30 ± 2.57
Exchangeable Na ($cmol_C$/kg air dry soil)	0.13 ± 0.01	Na^{+} (mg/L)	143.37 ± 31.23	113.68 ± 25.57	18.87 ± 5.51
SAR	1.53 ± 1.12	SAR	5.67 ± 0.21	4.08 ± 0.62	0.91 ± 0.15

Note: MBR, IDAL, and TW represent treated wastewater by membrane bioreactor system, treated wastewater by intermittently decanted aerated lagoon system and tap water, respectively. ± = SD (standard deviation), $n = 2$ & 12 for soil and water samples, respectively.

After removing roots and worms, the soil was air-dried and passed through a sieve (2.36 mm) before being packed in the columns. Ideally, soil particle size of 2 mm and less is considered as agricultural soil due to the inclusion of all primary mineral components (sand, silt, and clay). The majority of the reactive surfaces in soil are found within this range unlike the larger particles (rocks) that are not very reactive. The collected soil was of loamy-sand texture with saturated extract (pH_{SE}) and saturated extract electrical conductivity (EC_{SE}) of 5.9 and 0.55 dS/m, respectively. Some physicochemical properties of the soil are listed in Table 1 along with the similar parameters of irrigation waters. The relatively larger size of the columns used in this study compared with the common small lab-scale columns made it possible to minimize the errors such as wall effects by providing access to monitor the different parts of the columns with electrical equipment and taking soil-water samples from different depths. In fact, these types of columns are considered as an intermediate approach between lab scale small columns and field scale experiments (Abdou & Flury, 2004). However, the undisturbed soil in most of the field scale studies plays a major role in water flow and solute transport as these items are highly impacted by preferential flow and the spatial variation of soil properties (Abdou & Flury, 2004). In other words, when columns are packed with disturbed soils, the natural texture and the spatial heterogeneity are changed and can affect the water and solute flow behaviors (Abdulkareem et al., 2015). In addition, unlike the columns installed above the ground, field scale studies are mostly conducted equal to the ground surface with minimum space to the surrounding soils which keeps the microclimatic changes at a minimum level (Abdulkareem et al., 2015). Although these differences might not influence the suitability and validity of the results achieved from large column studies, it is necessary to be cautious when extrapolating the results to field conditions (Vereecken & Dust, 1998).

The columns were equipped with three GS3 sensors located at top, middle, and bottom of the columns (100, 300, and 500 mm depths from the top). These sensors measure bulk electrical conductivity, volumetric water content, and temperature every minute, and the determined data were collected and analyzed by a software program called PC200W. Adjacent to the sensors, pore water samplers were installed with a vertical 45-degree position to collect soil-water samples from different depths with the help of vacuum pumps. The obtained kikuyu grass from the nursery was laid uniformly on top of each column and was established under irrigation with the respective waters.

Characteristics of irrigation waters and initial soil

Three types of irrigation waters, namely, treated wastewater obtained from membrane bioreactor treatment system (MBR), treated wastewater obtained from intermittently decanted aerated lagoon system (IDAL) and tap water (TW) were used in the current study. MBR, IDAL, and TW were provided by Pennant Hills Golf Club's water resource recovery facility in Sydney, Sydney Water's Richmond STP (Sewage Treatment Plant) and drinking water supplied to the Sydney Metropolitan area by the Sydney Water Corporation, respectively. Detailed treatment process of each treated wastewater has been explained in Shahrivar et al. (2019). In brief, MBR system installed in Pennant Hills Golf Club, initially removes solids from raw sewage before going through biological reactions within anoxic and aerobic zones. The treated wastewater undergoes the process of ultrafiltration membranes followed by ultraviolet and chlorination processes just before being transferred to the water storage tanks. The treated wastewater, then, is used for the club irrigation needs, dramatically reducing municipal potable water use by conserving 94,600 m^3 of drinking water per year.

On the other hand, by implementing IDAL system, Richmond STP provides an annual amount of 115 ML recycled water for irrigation of Richmond Golf Course and 531 ML for irrigation of farms, parks, and sports fields within the Hawkesbury campus of Western Sydney University (Sydney, 2018). To overcome the less efficiency of the IDAL system on P removal (unlike N), the preliminary treated wastewater undergoes an addition of spent pickle liquor in an anaerobic zone. As an acidic mixture remained after metal treatment, spent pickle liquor contains iron sulphate, which under reaction with phosphorus forms iron phosphate. Iron phosphate is later removed from the wastewater in the settling unit and either disposed as sludge or forms seed sludge after returning to the anaerobic zone. Figure S1 summarizes the process of wastewater treatment through the IDAL system.

Soil sodium adsorption ratio is the determination of Na content relative to Ca and Mg in the water extract from saturated soil paste (Nrcs, 2017). The evaluation of SAR in soil extracts provides the characterization information for any saline condition. It is calculated as equation (1):

$$SAR = Na^{+} / \sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2} \quad (1)$$

where concentrations of Na^{+}, Ca^{+}, and Mg^{+} are measured in water extract from saturated soil paste and are expressed in meq/L (Rengasamy, 2010). Generally, soil SAR under irrigation with various types of wastewaters ranges between 4.5 and 7.9 (Feigin et al., 2012).

The exchangeable sodium percentage (ESP) is considered as part of a standard soil test in determining the soil sodicity. It measures the proportion of cation exchange sites occupied by sodium and is determined as Equation (2):

$$ESP = 100 \times Na/CEC \quad (2)$$

where, ESP is exchangeable sodium percentage of the soil expressed as percent, Na is the measured exchangeable sodium of soil with the unit of $cmol_c$/per kg air-dry soil and CEC is cation exchange capacity of soil which is the sum of exchangeable cations in the soil expressed as $cmol_c$/kg air-dry soil, Na included. Soils with an ESP of greater than 6 are considered as sodic, whereas ESP of greater than 15 is a characteristics of a highly sodic soil (Overheu et al., 2019).

The two treated wastewaters are similar in relation to their salinity levels, however, due to the effective nutrient removal by IDAL treatment system, it has lower concentrations of total nitrogen (TN) and total phosphorus (TP) compared with MBR system which may be considered as the main difference between the two treated wastewaters. The mean values of some selected parameters of three types of irrigation waters along with initial soil characteristics are given in Table 1. Following the mechanical texture analysis method described in Mcdonald et al. (1990) in conjunction with the soil textural triangle adopted in Australia (Soil et al., 2009), the soil was classified as loamy sand with 88.1%, 6.0%, and 5.9% of sand, silt, and clay, respectively.

By comparing the values of EC and SAR of irrigation waters with the guidelines stated in Ayers and Westcot (1985), it is evident that the soil sodification risk is placed in the slight to moderate range.

Irrigation scheduling

The data collected from the weather station installed in the site in conjunction with that of the soil sensors placed in different depths of the columns, helped to identify the interval of the irrigation events and the amount of applied water.

To avoid leaching of water and plant soluble nutrients because of excess application of irrigation water and to prevent any water stress to the plant, soil moisture content, particularly for the topsoil, was maintained above 15%. This was to keep up with the reputation of loamy sand to have roughly 10% and 20% of wilting point (WP) and field capacity (FC), respectively. Irrigation scheduling and climatic conditions has been discussed in more detail in Shahrivar et al. (2019).

Irrigation waters and extracted water from various depths

Electrical conductivity (EC) and pH for waters of different sources were measured using HQ40D Multi Meter (Hach, 2020). Total nitrogen (TN) and total phosphorus (TP) were measured simultaneously through persulfate method presented in (Rice et al., 2012). Digested samples were analyzed using the discrete analyzer (Gallery, Thermo Fisher Scientific) in the form of NO_X-N (NO_2^- and NO_3^-) and PO_4^{3-} for TN and TP, respectively. Main cations, including calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na), were measured directly using inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent Technology 700 series).

Kikuyu grass analysis

Grass from each column was harvested regularly every month and transferred to the laboratory for analyses. The fresh grass was weighed and rinsed with distilled water before being spread into the stainless trays. The trays were left at room temperature for 48 h in a dust-free environment before being placed into an oven of 70°C for almost 48 h until the weight of dried grass stayed constant. Dry grass, then, was ground and passed through the sieve of 0.5 mm for further analyses. TN and TP were measured following Method 7A2b (Total soil-N, semi micro Kjeldahl-automated color, FIA) explained in Rayment and Lyons (2011). Using concentrated H_2SO_4 plus anhydrous sodium sulphate (Na_2SO_4) raise the temperature to around 375–400°C and convert N and P in samples to NH_4^+ and PO_4^{3-}, respectively, over 180 min. For cation analysis (Ca, K, Mg, and Na), grass samples after digestion with a mixed HCl and HNO_3 acids of 1:3 ratios, were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent Technology 700 series).

Soil analysis

The entire soil from 0 to 50, 50–100, 100–200, 200–300, 300–400, 400–500 and 500–600 mm depths of the columns were collected after dismantling the columns at the end of the study. The collected soils were spread and dried onto clean plastic sheets at room temperature until the dried mass became constant. Using a sieve size of 2.36 mm (selected due to the initial soil particle size of maximum 2.36 mm), the remaining root parts were separated from the dried soil samples, and samples were taken from the dried soils at each studied soil depth. Soil TN and TP were measured using the method described in Rayment and Lyons (2011) through Kjeldahl digestion followed by discrete analyzer (Gallery machine, Thermo-Fisher Scientific). Soil exchangeable and soluble cations, saturated extract electrical conductivity (EC_{SE}), and pH (pH_{SE}) were analyzed using the methods provided in the same reference (Rayment & Lyons, 2011).

Statistical analysis

Analysis of variance (ANOVA) was carried out to determine whether there were any statistical differences amongst the three treatments regarding various variables. The t-test followed this to identify the level of differences between two different treatments. Typical *p* values used to identify whether the differences between the treatments were extremely significant ($p < 0.001$), significant ($p < 0.05$) or insignificant ($p > 0.05$).

RESULTS AND DISCUSSIONS

Applied nitrogen, phosphorus, and main cations

Application of irrigation waters was proportional to the soil moisture content at various depths of the columns and grass production rate from each column, resulting in slight difference in the volume of the applied waters throughout the study period. Table S1 summarizes the annual amounts of irrigation water, TN, TP, and main cations applied to the different columns. The amount of nutrients and cations applied to each column is calculated using the volume of respective irrigation water (Table S1) in conjunction with the average concentrations of each element presented in Table 1.

It can be seen from Table S1 that due to the relatively high concentrations of TN and TP, the soil irrigated with MBR treated wastewater received the highest amounts of these nutrients. The second highest amounts of TN and TP applied to the column irrigated with IDAL treated wastewater, whereas TW irrigated column received the least amounts of TN and TP. Except for Ca, the columns irrigated with both treated wastewaters received significantly larger amounts of cations, particularly Na, compared with the column irrigated with TW.

TABLE 2 Average nutrient content of kikuyu grass irrigated with different waters.

	TN (g/kg DM)	TP (g/kg DM)	Ca (g/kg DM)	K (g/kg DM)	Mg (g/kg DM)	Na (g/kg DM)
MBR	21.99 ± 2.4	3.75 ± 0.5	2.19 ± 0.2	17.98 ± 2.6	2.26 ± 0.3	1.47 ± 0.5
IDAL	20.38 ± 3.2	3.56 ± 0.5	1.64 ± 0.3	16.41 ± 2.7	2.52 ± 0.3	0.96 ± 0.2
TW	22.70 ± 2.4	4.34 ± 0.6	2.37 ± 0.2	17.08 ± 2.4	2.36 ± 0.4	0.48 ± 0.2
p-value	0.414	0.035	$1.45*10^{-5}$	0.485	0.342	$3.11*10^{-5}$
Literature	23.79 ± 7.2	3.5 ± 0.2	3.2 ± 0.2	33.7 ± 3.4	2.8 ± 0.2	0.6 ± 0.1

Note: MBR, IDAL and TW represent treated wastewater by membrane bioreactor system, treated wastewater by intermittently decanted aerated lagoon system and tap water, respectively. ± = SD (standard deviation), $n = 12$.

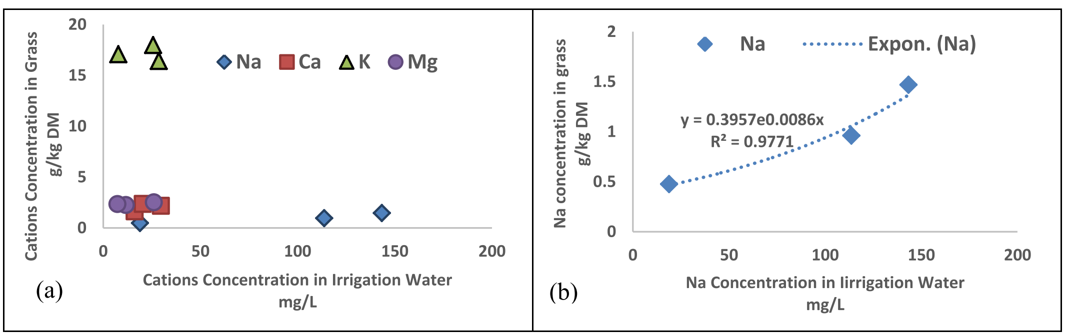

FIGURE 2 Variation of all cations (a) and Na (b) concentration between grass dry matter (DM) and irrigation water.

Nutrient uptake by kikuyu grass

Table 2 presents the average contents of selected elements in kikuyu grass throughout the study period. The presented value for each element is the average of 12 harvests. As seen in Table 2, the nutrient contents in the grass were roughly within the average range reported in the literature (García et al., 2014; Marais, 2001) except in the case of sodium which almost tripled and doubled when the grass was irrigated with MBR and IDAL treated wastewaters, respectively. It seems that kikuyu grass performs selectively in terms of sodium uptake. In contrast, for the other elements there was no obvious evidence of selective performance despite the availability of specific element in a large amount in irrigation water. This is illustrated in Figure 2. As it can be seen in the figure there was a clear correlation between the plant Na concentration and that of irrigation water. Whereas, for other cations (Ca, K, and Mg), it was not the clear (Figure 2a). Also, it appears that the Na concentration in the grass dry matter increases exponentially with the concentration in irrigation water (Figure 2b). Application of additional N to sodic soils up to 25% more than the required amount of N for non-sodic soil has been reported to compensate for the excessive amount of Na improving the yield and growth rate of the plant (Gupta & Abrol, 1990).

Carrying out the analysis of variance (ANOVA) followed by the *t*-test between the treatments showed various levels of differences (based on the *p* values) in the grass nutrient contents under each treatment. In detail, grass contents of TN, K, and Mg showed no statistical difference with *p* values bigger than 0.05 over the study period when irrigated with different waters regardless of their substantially different values in different irrigation waters (p: 0.414, 0.485, and 0.343 for TN, K, and Mg, respectively). In terms of TP, grass irrigated with treated wastewaters did not differ considerably ($p = 0.18$), whereas there were significant differences ($p < 0.05$) between the TP content of treated wastewaters and tap water irrigated grasses. One possible reason for this could be the interfering role of salinity with the grass P uptake regardless of higher P contents in the treated wastewaters, particularly in MBR, compared with TW. This idea is supported by other researchers who have reported the negative impact of salinity on P uptake (Grattan & Grieve, 1998; Khan et al., 2018). This, also might be one of the main reasons for higher grass production in the column irrigated with TW compared with IDAL treated wastewater (where 16,241, 7028, and 14,216 kg DM/ha of grass was yielded from the columns irrigated with MBR, IDAL and TW, respectively; Shahrivar et al., 2019).

An extremely significant difference ($p < 0.001$) appeared in grass Ca content by comparison of the grasses irrigated with MBR and IDAL and comparison of the grasses under IDAL and TW treatments, whereas Ca content did not change significantly ($p > 0.05$) when compared between the grasses irrigated with MBR and TW. This can be attributed to the concentration of Ca in irrigation waters and grass growth rate. IDAL irrigation water has lower Ca concentration than MBR and TW, which may result in lower concentration of Ca in its relative grass. Grass growth rate, also, plays a role in Ca uptake by the grass where the concentration of Ca in kikuyu grass has been reported to be a function of its production rate (Awad et al., 1976).

The grass growth rate produced with IDAL water was far lower than that grown with MBR and TW, especially in summer, where the kikuyu grows much faster than the other seasons (Shahrivar et al., 2019). This may result from high Na content in conjunction with the lack of vital nutrients such as N and P in the irrigation water obtained from IDAL treatment system. Finally, the statistical analysis in terms of Na revealed a significant difference ($p < 0.05$) between the grasses irrigated with the two treated wastewaters (MBR and IDAL) and an extremely significant difference ($p < 0.001$) between the grasses under irrigation with both treated wastewaters and TW. In fact, analysis on kikuyu grass from different columns showed considerably higher values of more than 200% and 100% of Na content in the grass structures grown using MBR and IDAL treated wastewaters, respectively, when compared with the TW column. However, the values were still far less than the damaging threshold for kikuyu grass, which is given in Radhakrishnan et al. (2006).

Changes in some soil physicochemical properties

Soil pH and EC

A comprehensive discussion on soil pH and EC and their possible effect on kikuyu grass production have been presented in Shahrivar et al. (2019). Figure S2a and Figure S2b present pH and EC of saturated soil extract versus the depth of different columns, respectively. In a nutshell, pH for the soil irrigated with IDAL stood higher than the two other soils under MBR and TW irrigation with values over 7. This made the ambient slightly alkaline, which has been reported as an undesirable pH value for kikuyu grass production. This could have been one of the main reasons for lower production of kikuyu grass in the column irrigated with IDAL compared with other two treatments (Shahrivar et al., 2019). In terms of salinity, EC_{SE} for wastewater-irrigated soils, compared with the soil initial value (0.55 dS/m), almost doubled with a

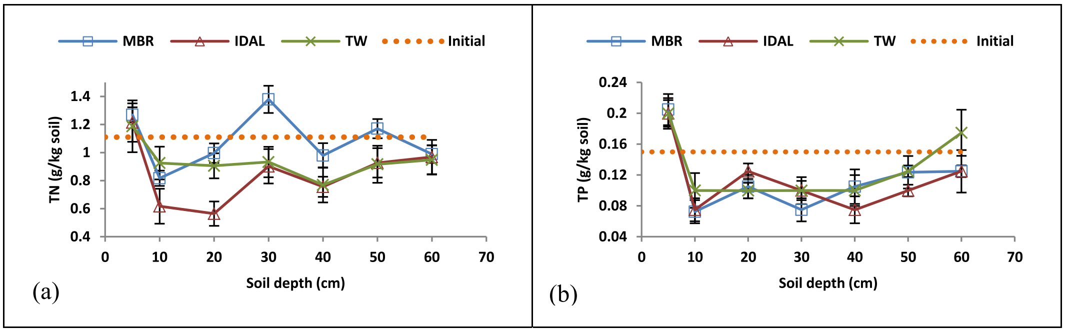

FIGURE 3 Soil TN (a) and TP (b) versus different depths of the columns irrigated with membrane bioreactor treated wastewater (MBR), intermittently decanted aerated lagoon treated wastewater (IDAL) and tap water (TW), $n = 2$; error bars: standard deviation; p-value (TN) = 0.083, p-value (TP) = 0.797.

noticeable increase in top 5 cm of the columns (around 2.5 dS/m). In contrast, no considerable change occurred for the soil irrigated with tap water. Prolonged use of recycled water may increase the EC of soil. This can be managed using options suggested by Rahman et al. (2015).

Soil TN and TP

Soil TN versus various depths in the columns under application of three types of irrigation waters is illustrated in Figure 3a. In 0–5 cm depth of all three columns irrigated with MBR, IDAL, and TW witnessed an inconsiderable increase in their TN contents compared with the initial TN value of 1.11 g/kg soil. Similar results are present in the literature for N increase in top soil when treated wastewater used for irrigation (Mohammad & Mazahreh, 2003; Rusan et al., 2007). The fertility level of the soil from various depths irrigated with MBR was generally improved compared with the other two columns under IDAL and TW treatments. Other researchers also have reported similar results for soil nitrogen increase under irrigation with secondary treated wastewaters (Abdel-Aziz & Abs, 2015; Ladwani et al., 2012).

Although TN in the soil irrigated with TW witnessed an insignificant change versus depth, IDAL experienced a sharp drop in its TN content compared with the soil initial value, particularly in 5–20 cm depth. Yet the TN values across the depth of the soil were not statistically significantly different ($p > 0.05$) between the treatments.

It seems that the lower concentration of N in IDAL wastewater compelled the plant to drain more N from the soil compared with other treated wastewater, MBR, which provided the soil and plant with just sufficient N. Another possible scenario could be the leaching of N in the column irrigated with IDAL. Analysis of leachate from the columns on extensive rainfall events showed higher loss of N from IDAL column in comparison to the other two treatments. One possible reason for this could be the higher nitrate content (easily leachable nitrogenous form) in the IDAL treated wastewater compared with that of MBR in which ammoniacal nitrogen predominates (nitrogenous form that is not easily leachable as it adheres to the soil). However, the leachate concentrations of nutrients were not proportional to the applied amounts by irrigation waters. However, no considerable N loss has been reported in the literature for the soil with moderate salinity under turfgrass (Bowman et al., 1999; Bowman et al., 2006).

In terms of TP, as shown in Figure 3b, no significant changes were observed for the depths of the columns except the top 5 cm which similar to TN in this area experienced a minimal increase compared with the soil initial TP value of 0.15 g/kg soil. The findings across the depth of the soils under various irrigation waters were, also, statistically insignificant ($p > 0.05$). Increase in soil P, particularly topsoil, when irrigated with recycled wastewater compared with tap water irrigation has been reported by other researchers in the past (Castro et al., 2013; Gwenzi & Munondo, 2008; Qian & Mecham, 2005). On the other hand, some others like Heidarpour et al. (2007) reported no significant differences in the soil P under irrigation using treated wastewater and drinking water.

Insignificant change in soil TP can be attributed to the very low concentration of P in IDAL and TW irrigation waters which could not benefit the soil fertility in terms of TP. Regarding MBR, gradually addition of this nutrient to the soil over the study period provides the plant with a continuous source of nutrient over the year with low chance of P accumulation in the soil structure. This can contribute to better kikuyu grass production where kikuyu grass has been reported to response well to the sufficient presence of P in the soil (Marais, 2001). The application of common fertilizer in a bulk form, which generally occurs once or twice a year, can cause accumulation, runoff or leaching of the nutrients. Leaching loss of soluble forms of

N in soil occurs at higher rates compared with P and K which have less mobility and strong connections to the soil and other elements (Islam et al., 2014; Wyatt et al., 2019). Hence, P and K are commonly applied to the soil in a single dose whereas nitrogen application occurs up to three times in a year. However, the level of nutrients available in irrigation water, type of soil, and irrigation management may resulted in variation in obtained results by different researchers (Mohammad & Mazahreh, 2003).

Saturated soil paste moisture content and soluble cations

Obviously, plant–soil interactions are influenced by the nutritional status of soil solutions and saturation extracts, including soil salinity and soil fertility (Rayment & Lyons, 2011). Due to the uniform texture of initial soil used in all the three columns the effect of irrigation waters on soil water holding property was evaluated by comparison the moisture content of saturation paste amongst the columns. Due to the strong correlation between FC, WP, and saturation percentage (SP), this can be an appropriate representative of actual soil-water-plant dynamics (Grewal et al., 1990). Figure S3 illustrates the water content of saturated paste for different columns versus the soil depth. As shown in the graph, there was no significant difference between the treatments at various layers of the soil ($p = 0.55$). Slightly higher values of SP in top 50 mm soil depth of each column could be the result of the increase in the soil organic matter in this area illustrated in Figure 3 with slightly higher TN and TP contents in topsoil of different columns.

Soils soluble cations versus the columns' depths irrigated with different irrigation water types are shown in Figure 4a–d. In terms of Ca (Figure 4a), no significant difference was observed across the soils depths of different columns. Soils of all three columns had a soluble Ca of approximately 3.5 meq/L in top 0–5 cm soil showing an increase of almost 50% compared with the initial soluble Ca value of 2.3 meq/L. However, the trend experienced a sharp drop for all three types of the soils in lower depths of the columns. This decline was not proportional to the initial concentrations of Ca in irrigation waters where they were different in this regard, particularly IDAL had very low content of Ca compared with MBR and TW. Considering the initial soil acidic ambient this may be considered logical where the most of the applied Ca by irrigation waters were retained in the top soil. Consequently, there was little soluble Ca that reached the deeper soil layers. Observed values were statistically insignificant across the depth under irrigation with all three types of waters ($p > 0.05$).

Bedbabis et al. (2014) reported a similar trend for calcium distribution versus the depth of the soil between the soils irrigated with tap water and treated wastewater in an olive orchard. In contrast to the current study, they observed a slight accumulation of Ca compared with the

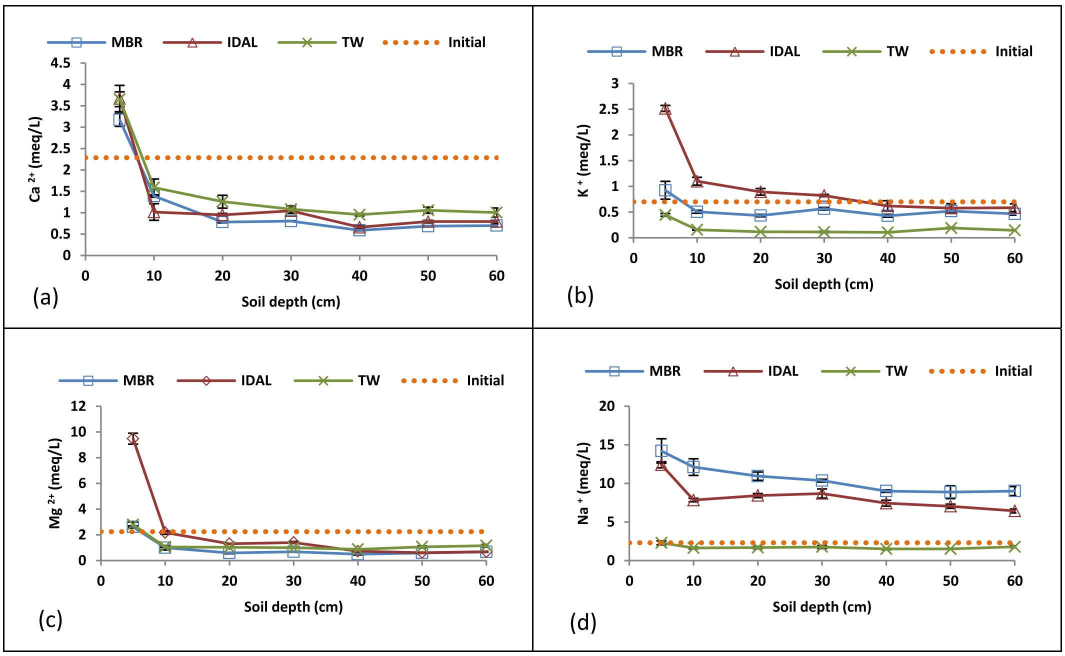

FIGURE 4 Soil soluble Ca (a), K (b), Mg (c) and Na (d) versus different depths of the columns irrigated with membrane bioreactor treated wastewater (MBR), intermittently decanted aerated lagoon treated wastewater (IDAL) and tap water (TW), $n = 2$; error bars: standard deviation; p-value (Ca) = 0.795; p-value (K) = 0.072; p-value (Mg) = 0.392; p-value (Na) = $1.5*10^{-8}$.

soil initial value, and they attributed this to the soil higher adsorption compared with the plant root uptake. In the current study, kikuyu grass behaved differently and showed more interest to take up Ca in competition with soil.

Soils soluble K across the depths of the soils irrigated with MBR, IDAL, and TW is illustrated in Figure 4b. It is obvious that soil irrigated with IDAL had the highest content of soluble K in its structure in all depths compared with the soils irrigated with the two other irrigation waters. Even though, availability of high values of K in IDAL irrigated soil during the summer did not stimulate the plant to take up more K than that of obtained by the other two grasses. This can be attributed to the excessive presence of the other cations in irrigation waters and soil structure particularly Mg and Na in IDAL. Yet obtained values of soluble K were not statistically significant across the depth when irrigated with the three types of irrigation waters ($p > 0.05$). Miles and Dugmore (1995) and Kemp (1983) reported that the availability of high N rate provided a generous uptake of K by kikuyu grass. A sufficient amount of N provided by MBR stimulated more K uptake. On the other hand, N deficiency in IDAL and TW irrigation waters may play the reverse role in this regard.

Figure 4c depicts the content of soluble Mg in soil structure across different depths of the columns irrigated with MBR, IDAL, and TW. Owing to the higher concentrations of Mg in the applied water (Table 1), IDAL irrigated soil contained the highest values of soluble Mg, particularly in the topsoil, approximately four times more than the soils irrigated with MBR and TW and is, also, almost four times the initial soil's soluble Mg value of 2.25 meq/L.

Moving to deeper soil layers revealed a decrease in soil soluble Mg compared with the initial value of soil soluble Mg in the soils irrigated with all three types of Irrigation waters. The accumulation of Mg in topsoil appears to be proportional to the concentration of Mg in the relative irrigation waters. Similar to soluble Ca, the initial acid soil with pH value of 5.9 may retain most of the Mg in the top soil, preventing soluble Mg from reaching the deeper layers of the columns. However, considering the Mg concentration of soil versus the depth, statistical analysis showed not significant difference amongst the various treatments ($p > 0.05$).

Figure 4d represents the distribution of soluble Na across the different depths of the soils irrigated with MBR, IDAL, and TW. Considering the average concentrations of Na in irrigation waters (Table 1), it is no surprise to witness the higher contents of Na in soils irrigated with treated wastewaters compared with the one irrigated with TW. Elevated levels of Na at the 5 cm depth are similar to the other cations observed (Figure 4a–c). Observed differences for soluble Na were statistically significant across the depth in all treatments ($p < 0.001$). Similar observations were made by several past studies (Bedbabis et al., 2014; Castro et al., 2013; Heidarpour et al., 2007; Mohammad & Mazahreh, 2003; Wong et al., 1995), who compared the soils irrigated with treated or untreated wastewaters to well water. Soil irrigated with TW maintained Na levels within the initial values. This shows that very little sodium is absorbed by the kikuyu grass when irrigated with TW.

Soil sodium adsorption ratio (SAR)

Figure S4 presents soil SAR across different depths of the soils irrigated with MBR, IDAL, and TW irrigation waters.

Close observation of Figure S4 and EC_{SE} values explained in Section 3.3.1 reveals no sign of salinity or sodicity in the soils irrigated with three types of water during the study period. Similar results were reported by Tahtouh et al. (2019) when treated wastewater was used for irrigation. However, the results provide statistically extremely significant differences between the soils under respective irrigation waters with $p < 0.001$. This can be obviously related to the presence of various cations in different values in three types of irrigation waters. In particular, higher concentrations of Na was observed in treated wastewaters (Table 1), resulting in higher values of SAR in the water extracted from saturated soil pastes. As mentioned before, EC of saturated extract of less than 4 dS/m in conjunction with SAR no more than 13, pose no risk for the plant growth and production, however they can retard grass production under the values close to the thresholds (soils under treated wastewaters in the current study) with the interference of other nutritional or environmental factors. However, from an agronomic point of view, the damage could be severe in many cultivated species if EC values exceed 2 dS/m.

Soil exchangeable cations

Exchangeable cations of soil are defined as those cations that can be exchanged by added cations (Thomas, 1982). Many of the nutrients used by plants are in the form of cations (Havilah et al., 2005). The concentration of available cations in the soil and the balance between them can cause imbalances, deficiency or toxicities. There is a strong relationship between soil cation exchange capacity (CEC), and physical (structural stability), chemical (nutrient availability), and biological (microbial population) characteristics of the soil (Khaledian et al., 2017). Therefore, determination of exchangeable cations and the ratios between them can be crucial in crop production and soil suitability to achieve a proper yield. This section will analyze the changes over any of exchangeable cations in detail.

The impact of irrigation with three types of irrigation water on soil exchangeable Ca is shown in Figure 5a. It can be seen from the graph that soil exchangeable Ca increased in various depths of the soils under application of all three irrigation waters at the end of the study. In detail, exchangeable Ca in top 5 cm of soils irrigated with MBR and TW went up similarly to approximately 4 $cmol_c$/kg air-dry soil compared with the soil initial value of exchangeable Ca. Exchangeable Ca of topsoil of the column irrigated with IDAL fell slightly behind the other two soils irrigated with MBR and TW. This can be attributed to the concentration of Ca in respective irrigation waters where MBR and TW contained higher amounts of Ca compared with IDAL. This increasing trend for Ca, particularly in top soil, was reported by Herpin et al. (2007) and Stewart et al. (1990) under secondary treated water irrigation. No significant differences were observed regarding the exchangeable Ca amongst the columns irrigated with the three different irrigation waters ($p = 0.62$).

Figure 5b shows the variation in soil exchangeable K irrigated with different waters at the end of the study. A surprising increase in soil exchangeable K occurred in the column irrigated with IDAL irrigation water where it enriched with nearly four times than the initial value of K.

This can be due to IDAL irrigation water's higher concentration of K. However, the average concentration of K in both treated wastewaters was very similar to develop such difference in soil K variation amongst the treatments. One possible reason to the accumulation of K in IDAL irrigated soil rather than being absorbed by grass could be the insufficient amount of N in the IDAL irrigation water. Such observation has reported in the literature (Kemp, 1983; Miles & Dugmore, 1995) where the availability of sufficient amount of N stimulated K absorption by the plant. This could be seen in MBR grass where more K was taken up by the grass owing to the higher value of N in MBR irrigation water. Variability of exchangeable K in the soil irrigated with TW was negligible compared with the soil initial value of exchangeable K. A part of increase in topsoil K in all three columns could be the result of grass debris after each harvest contributing to soil fertility (12 harvests).

A similar trend to soil soluble Mg was achieved for the exchangeable Mg after the period of study under different treatments. However, unlike soluble Mg, soil exchangeable Mg increased over the study period in different layers of the soil. Figure 5c illustrates the variation in soil exchangeable Mg at the end of the study.

By comparison, there are similarities between the graphs developed for soil exchangeable K and Mg. By considering the Table 1 and Figure 5c, it is evident that the variations of exchangeable Mg in different columns were almost proportional to the average concentrations

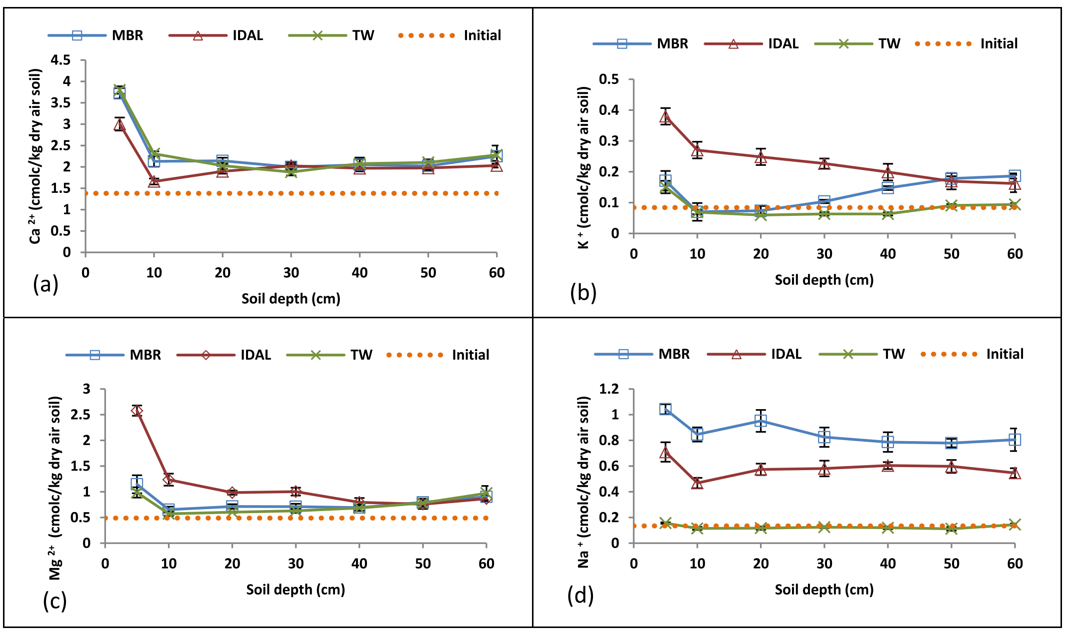

FIGURE 5 Soil exchangeable Ca (a), K (b), Mg (c), and Na (d) versus different depths of the columns irrigated with membrane bioreactor treated wastewater (MBR), intermittently decanted aerated lagoon treated wastewater (IDAL) and tap water (TW), $n = 2$; error bars: standard deviation; p-value (Ca) = 0.620; p-value (K) = $2.2*10^{-4}$; p-value (Mg) = 0.117; p-value (Na) = $7.6*10^{-13}$.

of this element in the irrigation waters. Topsoil irrigated with IDAL, experienced a considerable increase in exchangeable Mg compared with the soil irrigated with the two other irrigation waters and soil initial value.

Moving across the deeper layers of the soil, this trend descended gradually where the soils under different treatments experienced a negligible change over the study period. A similar trend was reported by Stewart et al. (1990) for different layers of the soil under irrigation with secondary treated wastewater. Herpin et al. (2007), reported no alterations in the soil layers over the 2 years of experimental period when they used secondary treated wastewater for irrigation. This can be the result of low concentration of Mg in the irrigation water compared with the treated wastewaters used in the current and Stewart et al. (1990) studies.

Soil irrigated with TW experienced no considerable alterations in its exchangeable Na content in different layers. In contrast, the other two soils irrigated with treated wastewaters revealed a substantial increase in their exchangeable Na compared with soil initial value. Figure 5d shows the alterations in soil exchangeable Na versus the different layers under various irrigation waters. As it can be seen from the graph, soils irrigated with both MBR and IDAL irrigation were affected in similar extents regarding the depth of the soil. However, MBR imposed a higher value of exchangeable Na on the respective soil perhaps due to the higher loading rate of Na and lower rate of Mg and K compared with IDAL. Sodium is considered as the main cation in wastewater compared with Ca, K, and Mg and tends to replace the other cations in the change complex. This means that the availability of excessive amount of Na can contribute to leaching of the other competing cations from change complex (Jalali et al., 2008). The result of leachate analysis over the study period showed higher amounts of K and Mg drained from the MBR column compared with IDAL which can support this idea (replacement of K and Mg by Na in cation exchange complex).

Changes in root dry matter and nutrient components

Root dry matter

The top 5 cm depth of each column accommodated the highest percentages of the total roots of the respective columns with 49.75%, 59.76%, and 58% for MBR, IDAL, and TW, columns, respectively. Distribution of root mass in the soil media of various treatments is shown in Figure 6.

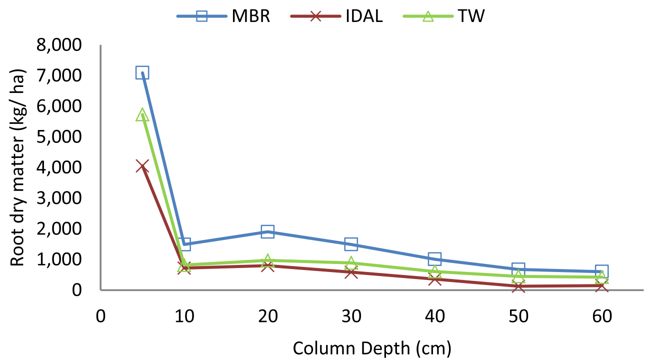

FIGURE 6 Root dry matter across different depths of the columns irrigated with membrane bioreactor treated wastewater (MBR), intermittently decanted aerated lagoon treated wastewater (IDAL) and tap water (TW).

As it can be seen, the highest dry matter of root obtained from the column irrigated with MBR throughout the soil depth. Irrigation under TW resulted in the second largest dry matter of root, and the smallest amount of root dry matter belonged to the column under irrigation with IDAL.

Total dry matter of 14,255, 6781, and 9884 kg/ha of root produced from the columns irrigated with MBR, IDAL, and TW, respectively. The trend was similar to that of grass production from different treatments (Shahrivar et al., 2019). This can be attributed to the characteristics of irrigation water and the changes occurred in the soil properties. The deepest part of the columns witnessed a very low root concentration for the column irrigated with IDAL which may be due to the low concentrations of vital nutrients in this irrigation water in the presence of a relatively high level of salinity, particularly when compared with TW. Muscolo et al. (2003) also reported a decrease in kikuyu grass root growth when high levels of salinity were in practice. Their findings revealed that kikuyu grass was able to tolerate up to 100 mM NaCl as a type of salt tolerant grass.

In the current study, the big gap between the root dry matters of treated wastewaters can be the result of lack of vital nutrients in the IDAL treated wastewater. In fact, the moderate salinity level in conjunction with nutrient deficiency seem to have the major role in lower root production in IDAL column. The difference between root production in MBR and TW columns may also strengthen the importance of TN and TP in overcoming the issues related to the soil and water salinity. In other words, the sufficient nutrient present in MBR seems to mitigate the severe effect of the moderate salinity level on both leaf and root production rates.

Nutrient contents of root versus the depth of the soil

Weighted average of the root components of the columns irrigated with various irrigation waters is given in Figure S5. Weighted average (WA) of each component is calculated as Equation (3):

$$WA = \sum_{n=1}^{n=7} C_n DM_n / \sum_{n=1}^{n=7} DM_n \qquad (3)$$

where n refers to the depth of the column where the sample is taken (for instance, $n = 1$ refers to 0–5 cm depth of the soil, $n = 2$ refers to 5–10 cm depth of the soil, etc.) and C_n is the concentration of the component in the root of the same depth and DM_n is the root dry matter. It can be seen from Figure S5 that except potassium, the rest of the components have been distributed in the root structure similar to kikuyu grass leaf. It appears that despite root interest in the absorption of K, its uptake by the leaf structure is limited in the column irrigated by IDAL treated wastewater.

CONCLUSION

Irrigation with treated wastewater has been associated with significant variation in soil and plant physicochemical properties. The sodium content in the grass irrigated using treated wastewater was significantly higher than in the control. However, the increased values did not exceed the plant's damaging threshold reported in the literature. This may encourage the use of treated wastewater for irrigation for this particular type of turf grass which is very popular and commonly used in sports fields, pastures, public areas, and golf course fairways. However, the accumulation of salts in various layers of the soil over the study period (1 year) revealed that it may cause serious damage to the plant by increasing soil Na and EC if the trial lasts for several years. That said, it seems necessary to increase the irrigation events and apply water to let salts leach to the deeper layers. In other words, this study indicates that the recycled water application needs to be more than what was determined based on the soil moisture to minimize salt accumulation. In addition, it is recommended to replace treated wastewater with tap water for irrigating the land at some regular intervals to control soil salinity and sodicity.

Another significant observation was the increased uptake of sodium by the plants. The highest uptake was by the plants irrigated with MBR treated wastewater which had the highest sodium concentration. This was followed by the plants irrigated with IDAL treated wastewater with relatively lower sodium concentration. The plants grown using tap water had the lowest sodium concentration. Thus, the results indicate that the sodium accumulation in the plant was proportional to its concentration in the irrigation water.

The data on the soil soluble cations and exchangeable cations in each column showed very similar trends for the soil depth over the study period. The topsoil of the columns irrigated with treated wastewaters indicated higher values of sodicity compared with the soil irrigated with tap water (TW). However, the observed sodicity values were considered to be moderate for kikuyu grass production based on the information reported in the literature. Nutrient and cation analyses of kikuyu grass leaves and roots in each column showed fairly similar composition in their structure. During the monitoring period (over 1 year period), no excessive accumulation of salt in the soil and grass was observed. Higher values of N and P in MBR treated wastewater not only can stimulate grass production, but it can also yield several other benefits. The benefits include saving in wastewater treatment related costs, saving in the application of inorganic fertilizers, saving precious drinking water, and preventing environmental contaminations through wastewater discharges and agricultural runoff into receiving waters.

AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Formal analysis, Data curation, Writing—original draft, Writing—review and editing, Software: Alireza A. Shahrivar. Conceptualization, Methodology, Data curation, Writing—original draft, Writing—review and editing, Supervision: Dharmappa Hagare. Methodology, Writing—review and editing, Supervision: Basant Maheshwari. Conceptualization, Methodology, Data curation, Writing—original draft, Writing—review and editing, Supervision: Muhammad M. Rahman.

ACKNOWLEDGMENTS

The authors wish to acknowledge the Pennant Hills Golf Club operators in particular Kurt Dahl and Richard Kirkby of Permeate Partners Pty. Ltd. for providing access to collect MBR treated wastewater. The authors also are grateful to Dr Roger Attwater and Dr Lyn Anderson for their assistance in collecting IDAL treated wastewater. Environmental engineering lab staff contributions at Penrith campus of Western Sydney University and Louise Prouteau, an internship student of ENSCR, France, are gratefully acknowledged. Open access publishing facilitated by Western Sydney University, as part of the Wiley - Western Sydney University agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors have no competing interests to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Shahrivar, A. A., Hagare, D., Maheshwari, B., & Rahman, M. M. (2023). The impact of irrigation with treated wastewaters on soil and kikuyu grass nutrient compositions. *Water Environment Research*, *95*(6), e10873. https://doi.org/10.1002/wer.10873