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Original Article

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Feasibility of natural wastewater treatment systems and life cycle assessment (LCA) for aquatic systems

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Abstract

Background: Natural wastewater treatment systems (NWTSs) in small villages are a major challenge for European water authorities. With growing social demands for environmental practices, evaluating the feasibility and environmental impact of low-cost treatment systems for small residential areas is essential.

Methods: To address this challenge, this study was conducted to evaluate 10 NWTSs seasonally in rural areas of Bursa, Turkey. Authorities over the facilities permitted the examination of workable, low-cost effluent management options. Also, using Open-LCA software based on ReCiPe MidPoint (H) version 1.67, these plants' effects on global warming, Phosphorus-depletion, human toxicity, marine eutrophication, and freshwater eutrophication were examined.

Results: According to the LCA findings, Deydinler NWTS had a greater impact across all three effect areas (freshwater eutrophication, marine eutrophication, and human toxicity), ranging from 11 to 41%. Pinar and Yenice facilities, however, had 26% and 27% larger impacts in the same two impacts (marine eutrophication and human toxicity). These systems performed on average at 67%, 50%, and 58% chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) elimination, respectively.

Conclusion: According to the findings, 10 NWTSs have a treatment efficiency of about 70%. NWTSs are possibilities for decentralized wastewater treatment in small residential areas that are both cost-effective and environmentally favorable. By treating organic pollution naturally, without chemicals, and with minimal energy use, they lessen their negative environmental effects. The main findings of this study will be useful for academics in determining future research areas and identifying whom they might consult to help design carbon footprint of NWTS and future carbon reduction objectives.

Keywords: Freshwater, Sewage, Water purification, Life cycle stages, Wetlands

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Introduction

Recently, seeking solutions for environmental protection in rural areas has increased, particularly regarding sewage treatment (1). Domestic sewage from decentralized sewage systems in rural areas is often directly discharged into receiving water, causing undesirable environmental and public health problems. The main pollutants that impair the quality of surface and groundwaters in rural areas are typically suspended solids, organic materials, pathogenic wastes, and animal wastes (2-5). In making operational decisions, it is important to establish discharge guidelines and take wastewater quality into consideration (6,7). Depending on their capacity, technology, and treatment methods, wastewater treatment plants can have a direct impact on human health (8-10). The primary goal of wastewater treatments is to create effluent that is appropriate for discharging into receiving environments, ensuring that effluent discharge criteria are met and that the receiving ecosystems suffer no losses as a result (11). However, due to high investment and running expenses, it is impractical to build sewage treatment plants in rural areas with low population density and a fragmented sewerage network (12). Constructed wetland tanks are one type of natural treatment systems used in rural areas, offering low-cost and excellent treatment efficiency for small settlements, wastewater flows towards the filtration mechanism where it is chemically free-treated (13,14). Despite their inefficiency in the case of insufficient design and construction deficits, these systems are the best alternatives to wastewater treatment for rural areas that do not provide a water treatment service and discharge directly to the surface and groundwater sources (5).

The Turkey's State Planning Organization's Rural Development Strategy Report (2017-2023) states that the development of natural treatment plants should be prioritized due to their low construction and operating costs to eliminate the need for a central sewage system (15,16). It suggests an environmentally friendly, cost-effective, and labor-efficient solution with high public acceptance for wastewater treatment in small residential, rural areas with low population density in Turkey. Among the 888 wastewater treatment systems in Turkey, 53 are physical, 494 are biological, 141 are advanced, and 200 are natural (17).

There are 12 municipal wastewater treatment plants and two marine outfall facilities in Bursa, Turkey. Natural wastewater treatment systems (NWTSs) are used to eliminate wastewater in small settlements with fewer than 1000 residents that are not connected to the Bursa's central sewage systems. Although the precise number of these systems is uncertain, 53 natural wastewater treatment facilities are run by the Metropolitan Municipality of Bursa (16). Despite the widespread use of natural treatment methods, little research has been done presenting their environmental effects. The assessment of the environmental impact of natural treatment systems in rural areas will help the decision-makers and will guide future steps with the sustainable operation of the wastewater treatment systems. Due to the limited alternatives available, NWTS and constructed wetlands (CW) with comparable treatment processes are relatively prevalent, especially in small settlements of developing countries like Turkey and Brazil (5,18,19). These facilities also enhance the quality of treatment plants in organic matter removal for primary, secondary, and tertiary treatment, particularly in rural areas (5,20,21). CW and NWTS are provided in European and Central European countries through the Global Water Partnership program for the remaining 10% of the rural population (about 20 million people) (16).

Life cycle assessment (LCA) is an effective tool to evaluate wastewater treatment plants through environmental impacts (1,22,23). It is crucial to incorporate LCA methods into these facilities' strategic plans, especially in developing countries and rural locations (24). Several LCA researches on different centralized or decentralized wastewater treatment systems emphasize that various factors, such as influent composition, system scale, electric consumption, and seasonal climatic changes affect assessments (25-29). Moreover, studies have been recently done in central wastewater treatment plants, the effectiveness and environmental impact of decentralized facilities are less prevalent and have started to steadily increase (30-37).

The latest research shows that wastewater treatment and water supply plants may also have environmental impacts, but the best alternatives should be chosen by the benefit/cost impact (38-42). In recent years, the rapid use of professional software designed for LCA research, which has a user-friendly database backed by artificial intelligence, quick results, and comparative benefits, is rising (43). While the most widely used programs are SimaPro and GaBi, OpenLCA has been preferred in recent years because it is cost-free and produces findings that are comparable to those of SimaPro and GaBi (44).

To guarantee the sustainability and effective operation of these infrastructures, many LCA tools have been applied in rural areas of Europe (5,45,46). According to the study of Lam et al, wastewater treatment management is essential in developing nations, and the situation is particularly dire in rural areas (32). Klöpffer and Curran highlighted the value of LCA-based studies in some nations, such as Turkey, where LCA logic is not ingrained (47). In Turkey, it is very difficult to locate high-quality research for compilation and application (48-53). The lack of LCA analyses on the central wastewater treatment plants in developing countries such as Turkey and the fact that there is a gap in examinations regarding NWTS, make this study a pioneer (5,48,54).

In this study, the seasonal treatment performances of 10 NWTSs in Bursa city, which has a population ranging from 400 to 1500, were assessed. Using OpenLCA in rural areas, LCA analysis was utilized to evaluate how the systems' environmental effects might improve sustainability solutions. Several topographical (rocky, mountainous, rough, sensitive places, etc) and wastewater characteristics in Bursa, Turkey, were taken into consideration when choosing NWTSs. The findings offer a seasonal benchmark for the systems' effectiveness and a review of the environmental effects of NWTS on wastewater produced in small residential areas.

Materials and Methods

System boundaries

The facilities consist of 10 natural wastewater treatment plants operated and maintained for over 20 years. In seven treatment plants, wastewater flows into the septic tank following the infiltration area, while in three, it flows directly into the infiltration area. The water released after the treatment during flow is discharged immediately to the receiving environment (14).

In this study, 10 NWTSs receiving wastewater from small areas were selected to evaluate among 53 operated by Bursa Metropolitan Municipality based on their topographical and wastewater characteristics and operation method. The influent flow rates of NWTSs are between 60 000-225 000 L of wastewater per day. All systems comprise a 3-chambered septic tank that receives the wastewater inflow. In seven systems, the septic tank discharge goes through a pumping station to an NWTS and the other three by gravity (Figure 1).

A septic tank also functions as a pre-treatment unit by settling solid particles from wastewater while serving as an equalization tank. Infiltration beds are components of NWTSs, where the treatment process takes place. Treatment efficiency is directly proportional to the retention time. The operation mechanism of NWTSs is displayed in Figure 2.

Parameters such as the population, wastewater characterization, the system's distance to the municipal wastewater treatment plant, the sensitivity of the receiving environment and its distance from the NWTS, and the topographical features of the region were taken into consideration while selecting the NWTSs to be studied. The impact of the characterization of the discharged effluent from the chosen NWTSs on sensitive receiving areas was evaluated. Table 1 displays the population, energy consumption, and receiving areas for the discharges from the NWTSs.

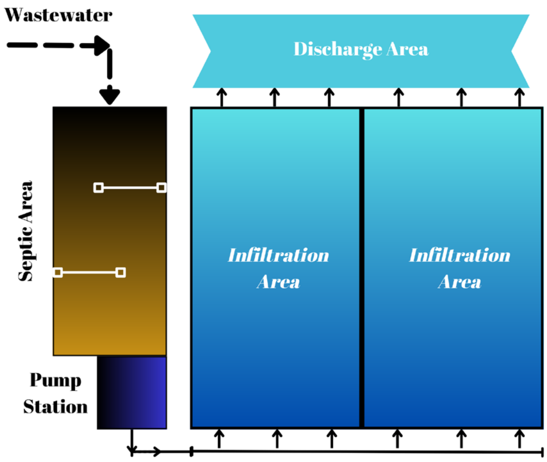

Figure 1. General flow chart and system boundaries of NWTSs examined within the scope of the study (6)

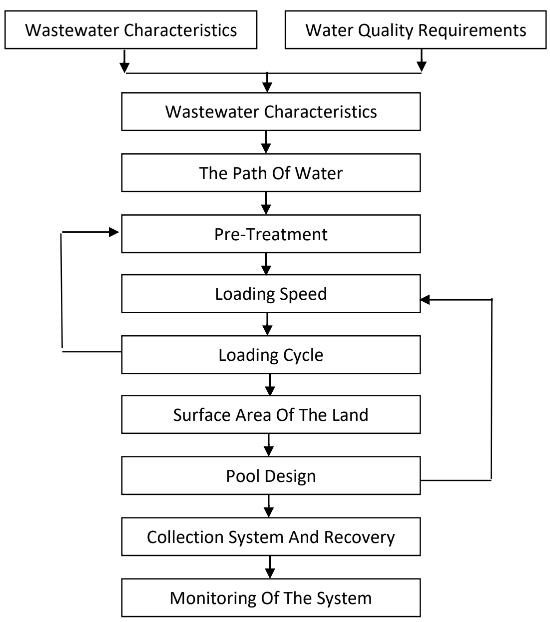

Figure 2. Design and operation management of natural wastewater treatment plants (16)

Sampling

The samples were collected seasonally for 270 days from the inlet and outlet of the NWTSs, including winter, spring, and summer, symbolizing warm, cold, and temperate air temperatures. In the province of Bursa, seasonal temperature changes ranged from -25.7 °C to + 42.60 °C (16,55). On the other hand, the average temperature values for winter, spring, and summer were 7.4 °C ± 0.7 °C, 15.2 ± 1.5 °C, and 21.1 ± 2 °C, respectively (16,55). A licensed laboratory (BUSKI Wastewater Laboratory) analyzed data to determine chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). 2-liter polypropylene containers were used for sampling. For seasonal correlation analysis, cooling degree day and heating degree day (HDD) acceptance standards of the country were taken as the basis; values of > 22.5°C for summer and < 15.5°C for winter were accepted. Regarding the average temperature values at which the samples were taken, statistical analysis was compared to hot and cold season conditions since there were no samples at the temperature values between HDD and cooling degree days (CDD) (55).

LCA and functional unit

The LCA systems were based on the ISO 14040 and ISO 14044 (ISO, 2006a, b) standards. This study modeled 10 NTWSs in OpenLCA based on ReCiPe MidPoint (H) (version 1.67). The impact categories considered were human toxicity, global warming, freshwater eutrophication, marine eutrophication, and P-Depletion, which were evaluated depending on the ReCiPe method. The operating parameters limit the system boundaries. Influence wastewater values, energy input flows, and discharge values output flows were assessed. Based on the literature, the functional unit was determined as 1 m^3 of treated wastewater (1).

In the context of LCA studies in wastewater treatment plants, the basic functional unit means that the wastewater treatment plant input values (e.g., COD, Total-N, and Total-P) are reduced to desired discharge criteria before being released into the receiving environment. Energy consumption, treatment efficiencies, and environmental loads were determined by associating them with the functional unit. In this research, the seasonal efficiency of natural treatment plants in removing pollutants was analyzed by collecting and analyzing input and output samples concerning COD, Total-N, and Total-P for three seasons. The electricity consumption of the pumps in the NTWSs was also determined based on the pumps' power and operating hours. In the inventory study performed in the LCA, the input components (e.g., influent

Table 1. Regions and equivalent populations of natural wastewater treatment plants

Natural wastewater treatment plants	Region	Population equivalent (pe.d)	Energy Consumption (kWh/year)	Discharged region/ discharged area
Ocakli Natural Wastewater Treatment Plant (NWTS1)	Mustafakemalpasa	1500	0	Susurluk/Susurluk Stream
Taspinar Natural Wastewater Treatment Plant (NWTS2)	Karacabey	400	0	Susurluk/Nilüfer Stream
Gurle Natural Wastewater Treatment Plant (NWTS3)	Orhangazi	750	39600	Marmara/Karsak Stream
Cicekli Natural Wastewater Treatment Plant (NWTS4)	Iznik	500	0	Sakarya/Kuru Stream
Yenice Natural Wastewater Treatment Plant (NWTS5)	Buyukorhan	1500	39600	Susurluk/Orhaneli Stream
Pinar Natural Wastewater Treatment Plant (NWTS6)	Buyukorhan	900	36000	Susurluk/Orhaneli Stream
Incirli Natural Wastewater Treatment Plant (NWTS7)	Yenisehir	680	36000	Sakarya/Kuru Stream
Mentese Natural Wastewater Treatment Plant (NWTS8)	Yenisehir	500	39600	Sakarya/Kuru Stream
Deydinler Natural Wastewater Treatment Plant (NWTS9)	Inegol	1500	39600	Sakarya/Kuru Stream
Alibeykoy Natural Wastewater Treatment Plant (NWTS10)	Inegol	1500	39600	Sakarya/Kuru Stream

wastewater analysis values and energy consumption) and effluent wastewater analysis values including sludge contamination, were used to determine the environmental load of the 10 plants.

When the study is evaluated within the scope of LCA, correctly determining the system boundaries is a significant parameter for the study's progress. System boundary variables are inputs, including raw material (CODin, Total-Nin, Total-Pin) and energy components, and outputs containing COD_{output}, Total-N_{output}, and Total-P_{output}.

Results

Seasonal efficiency performance

The rates of COD removal for the NWTSs ranged from 12% to 97%. The COD removal efficiencies for four NWTSs (Gürle, Cicekli, Pınar, and Yenice) were exceptionally high, calculated at > 70%, which is consistent with the discharge standards of Turkish Water Pollution Control Regulations (21). Figure 3 shows COD inflow and outflow concentrations for the NWTSs. The nutrient removal efficiencies of NWTSs were relatively high, especially for Pinar and Incirli NWTSs, which reached a removal rate of 100% for TN and TP (Figure 3).

As shown in Table 2, the effect of seasonal conditions on pollutant removal is observed in winter removal efficiencies, which are 10% lower than in summer. Conversely, TN and TP removal efficiencies are 34% and 46% lower, respectively. The correlation of seasonal removal efficiencies shows that COD removal has a partial meaning for $P \geq 0.05$ (data not shown). The statistical significance of the results is shown in Table 2. The investigation of the relationship of the season with the removal efficiency shows that there is no seasonal relationship in the pollutant removal efficiency (Table 2).

Evaluation and comparison of general parameters

In rural areas with insufficient wastewater treatment

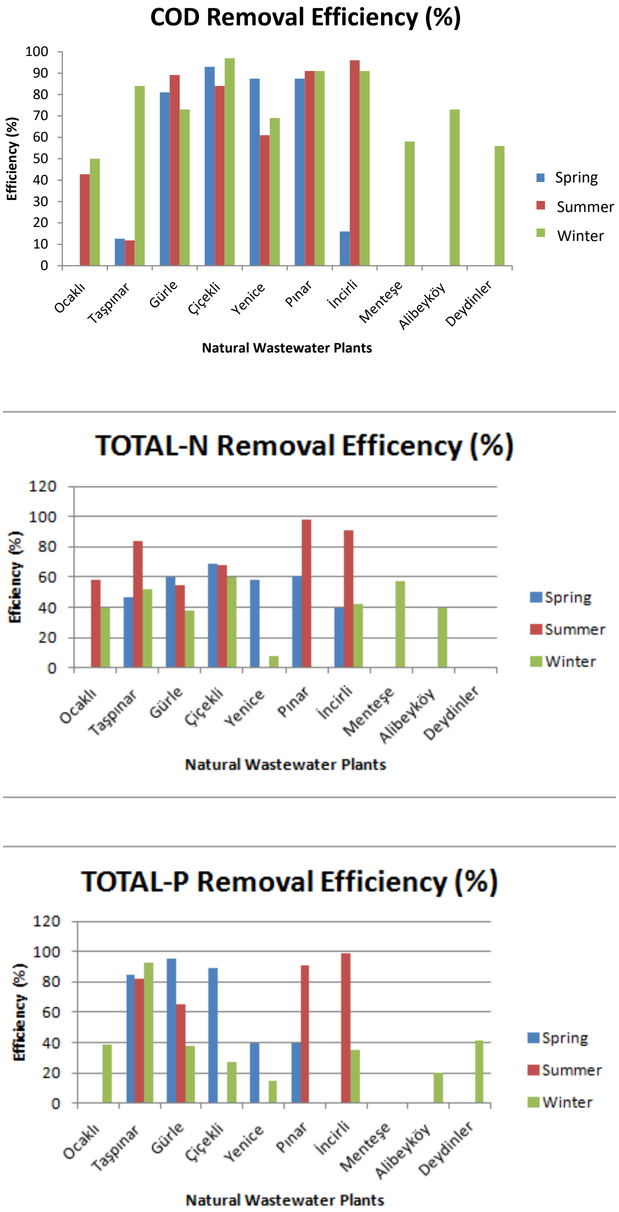

Figure 3. Seasonal COD, TN, and TP removal rates of 10 NWTSs

facilities, the removal efficiencies must correspond with the discharge standards. Turkish Water Pollution Control Regulation and the EU directives apply the necessary regulations to conserve receiving environments in the region. In this study, the effluent water quality was evaluated according to the discharge standards of Turkey and the EU. The influent and effluent parameters of NTWSs are shown in Table 3.

Among the investigated systems, Ocakli, Taspinar, and Yenice NWTSs do not meet the receiving environment discharge standards set by the EU and Turkey during winter (Figure 4).

Encountered challenges during the operation phase of the facilities, and their removal efficiencies were examined seasonally (Figure 5). The environmental impacts related to the infiltration area are for 67.5% average COD removal of the total impacts of these NWTSs. According to the results, COD, TN, and TP in the NWTS are responsible for most environmental impacts (Figure 5).

As the air temperature increases in the treatment processes of the plants, a rise in COD, T-P, and T-N removal efficiencies occurs. Although the average removal efficiencies of T-P and T-N are low in six facilities (<70%), they prevent high amounts of pollutant load when the population they serve is considered.

LCA results

The potential LCAs are shown in Figure 6. The impact is due to COD treatment and sludge disposal, considering human toxicity values. The investigated values display that Pinar and Yenice facilities have a higher effect (33.9% and 29.8%, respectively) than the other eight facilities.

Deydinler and Mentese plants have the highest effect (36.4% and 50.8%, respectively) on the environmental impacts of freshwater eutrophication (Figure 6). All the eight NWTSs (Ocakli, Taspinar, Gurle, Cicekli, Pinar, Yenice, Incirli, Mentese, and Deydinler) have an environmental impact of 12.8% regarding freshwater eutrophication. Marine eutrophication potentials were mainly affected by removing T-N. The overall environmental effects of the seven NWTSs (Ocakli, Taspinar, Gurle, Cicekli, Incirli, Mentese, and Alibeykoy) were relatively low (17.5%) in terms of marine eutrophication, while Pinar, Yenice, and Deydinler NWTSs had the highest environmental impact (17.8%, 23.8%, and 40.8%, respectively).

Concerning P-depletion potentials, a major impact was due to sludge transportation. Analysis of the results shows that Alibeyköy, Yenice, and Gürle facilities have a quite high impact compared to other facilities (74%).

According to the results, Pinar and Yenice NWTSs were responsible for most of the possible human toxicity (33.9% and 29.8%, respectively) and marine eutrophication (17.8% and 23.9%, respectively) impacts. The other eight NWTSs (Ocakli, Taspinar, Gurle, Cicekli, Incirli, Mentese, Alibeykoy, and Deydinler) had a lower environmental impact (36.3%) in terms of human toxicity. Pinar and Yenice NWTSs were also found to have a lower environmental impact (2.54% and 3.38%, respectively) with less association regarding their freshwater eutrophication. On the other hand, the Cicekli facility has the lowest human toxicity, marine eutrophication, freshwater eutrophication, global warming, and P-depletion effects (1%, 0.86%, 1.69%, energy-free, and 1%, respectively). Moreover, its organic

Table 2. Average removal in cold and warm weather conditions and correlation of seasonal performance

Pollutant	Session	Parameters	Values
	In cold weather	Average removal (%)	74.2
COD	In warm weather	Average removal (%)	81.8
		P value	0.062
	In cold weather	Average removal (%)	42
TN	In warm weather	Average removal (%)	76
		P value	0.652
	In cold weather	Average removal (%)	38.5
TP	In warm weather	Average removal (%)	84.2
		P value	0.403

Table 3. Water quality and data of NWTSs

NWTS	Parameters (average values of sampling period)							
	Flow rate (L d^{-1})	Energy (kWh)	COD ınfluent (mg L^{-1})	COD effluent (mg L^{-1})	Total-N influent (mg L^{-1})	Total-N effluent (mg L^{-1})	Total-P influent (mg L^{-1})	Total-P effluent (mg L^{-1})
Ocaklı	1,500	0	396	203	37	19	7	5
Taspinar	400	0	72	67	13	6	11	2
Gurle	750	5,5	130	23	7	5	6	1
Cicekli	500	0	388	25	46	16	5	3
Yenice	1,500	5,5	705	170	102	85	8	6
Pinar	900	5	914	42	86	39	8	4
Incirli	680	5	205	17	42	9	4	1
Mentese	500	5,5	280	193	30	22	22	5
Alibeykoy	1,500	5,5	76	21	86	51	7	6
Deydinler	1,500	5,5	257	61	176	30	81	3

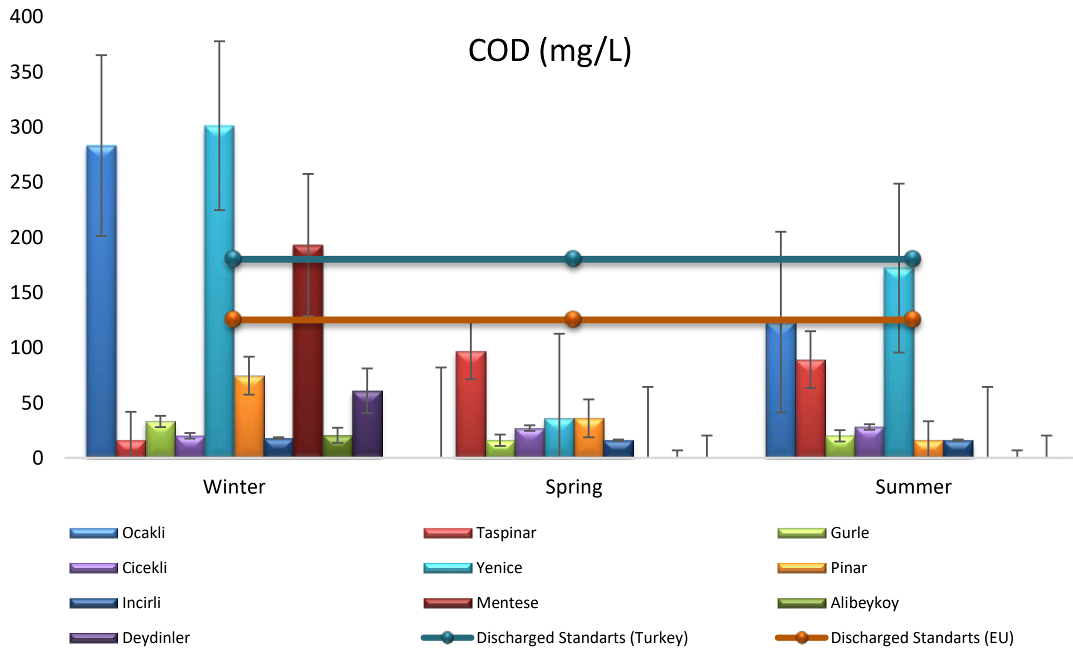

Figure 4. Comparative evaluation of the characteristics of the effluent of the systems with natural treatment systems discharge standards in Turkey (56) and the EU, according to COD (mg/L)

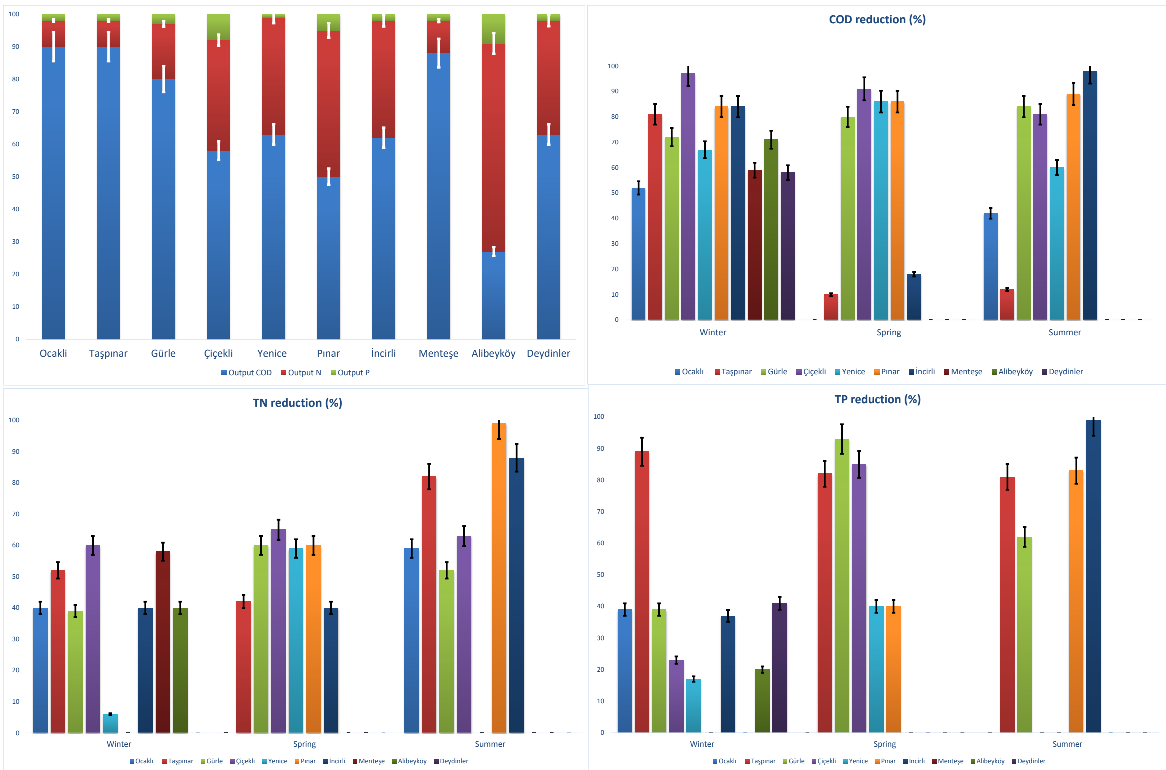

Figure 5. Reduction in the loading factors of the investigated NWTSs

matter removal efficiency is high (87.6%, 62.7%, and 54%, respectively).

The main advantage of NWTSs over central wastewater treatment plants is their energy consumption. The global warming effect of facilities is provided in Figure 6. In seven facilities, a pump is used as an energy source only to transmit water from the septic tank to the infiltration area, whereas this is not the case in three. The energy consumption and kg CO_2 eq values of the facilities per purified m^3 wastewater are shown in Figure 7.

Electricity consumption reveals that Gürle (1.17 kWh/m^3), İncirli (1.18 kWh/m^3), and Mentese (1.76 kWh/

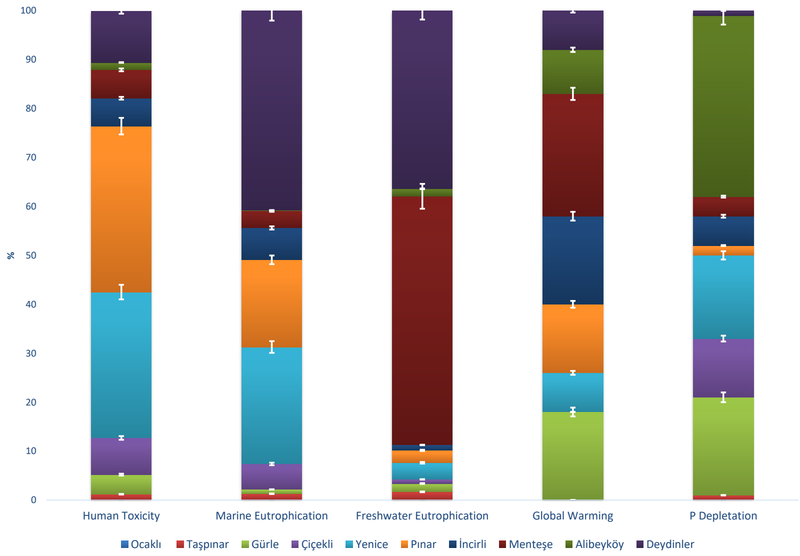

Figure 6. Relative life cycle impact of the investigated NWTSs

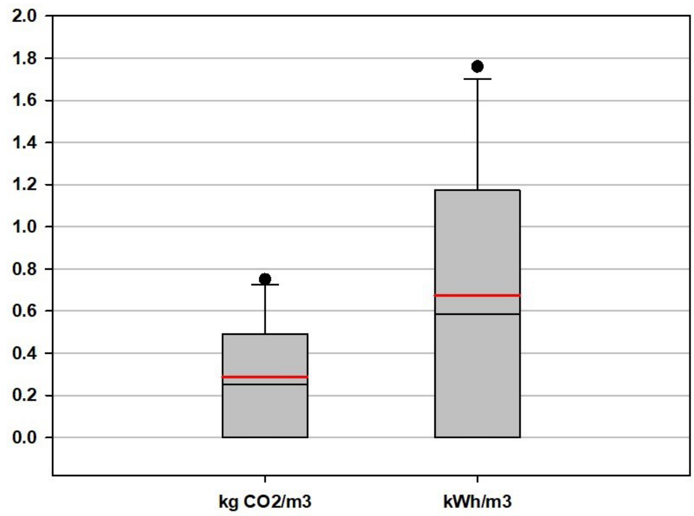

Figure 7. Electricity consumption and global warming potential

m^3) consume 30% more energy than other facilities. The electricity consumption of the other seven facilities is below 1 kWh. Looking at the CO_2 emissions due to the facilities' energy consumption (Figure 7, right), the highest carbon emission was determined at the Mentese facility (0.75 kg CO_2/m^3).

Discussion

In the present study, 10 NWTSs in Bursa, where Bursa Water and Sewerage Administration are operated, were examined to determine their seasonal environmental impacts and treatment efficiency. The results showed that removal efficiencies of three NWTSs (Gurle, Cicek, and Pinar) were relatively high for measured parameters (> 90% for COD, TN, and TP combined) and met legal discharge regulations. The improvements in maintenance and repair could reduce the environmental impacts of the facilities. The adsorption process in the NWTSs and microorganisms in the treatment structure allows COD removal. In addition, depending on the filtration and flow rate in plant stems, organic matter removal is also effective in COD removal (57). Studies on this subject have reached removal rates of 74.79%, 71%, and 78% in COD, Total-N, and Total-P in constructed wetlands (58,59). Horn et al declare that 97% COD removal of constructed wetlands, a highly effective treatment method, could be achieved (60). Furthermore, a study conducted in Iran reported 70% COD removal efficiency in stabilization pools (11).

Total nitrogen removal was relatively high in the summer season despite the low removal rates of TN in winter and spring. Denitrification is the first step in removing Total-N in NWTSs (59). The growth constants of nitrifying bacteria are greatly affected by temperature (61). It has been reported that the growth of Nitrosomonas and Nitrobacter in NWTSs was affected negatively by cold weather conditions by Tunçsiper (57). At temperatures below 15°C, the nitrification rate drops sharply and is lowered by 50% at 12°C (62). Cold weather decreased the TN removal rate in six NWTSs during spring and winter. In another wetland study, 40%-50% of treatment efficiencies were achieved depending on nitrification (59,63-65).

According to some studies, plant roots, directly and indirectly, remove phosphate compounds in constructed wetlands (66,67). In addition, some studies have declared that aerobic bacteria such as rhizosphere are effective in the uptake of nutrients (phosphate and nitrate) and oxygen transport (67-69). Replacing the adsorption gravel media of the system with an efficient media could be an alternative for reducing environmental impacts, especially TP; however, Lopsik (45) has found that the use of expanded clay as a gravel alternative has caused 10–42% more effects. The results of this study proved that NWTSs have low operating costs and are highly efficient in rural areas. These outcomes were compatible with the reported pilot-scale and full-scale systems, which typically range from 75% to 95% (70).

Statistical analyses showed that seasonal differences are also crucial for TN and TP removal rates. Several studies have investigated the effect of seasonal conditions on TP removal efficiency. In a study by Kadlec, a significant decrease in TP removal efficiency was observed in winter and spring (71). In contrast, Zhu et al (72) found that there was no significant difference in biochemical oxygen demand (BOD) and total suspended solid (TSS) between the cold and hot periods at nine central wastewater treatment plants in Norway.

Within the scope of the study, five potential environmental effects of the facilities (human toxicity, marine eutrophication, freshwater eutrophication, global warming, and P-depletion) were investigated. The LCA studies conducted in artificial wetlands stated that these facilities are environmentally friendly alternatives (14). According to recent research, fully or partially treated wastewater can cause eutrophication (27). Eutrophication of freshwater can also result from the mixing of wastewater and phosphates released during electric production with ground and surface water (29). When evaluated in terms of marine eutrophication and freshwater eutrophication, environmental effects can be strongly reduced by dewatering and reusing sludge compared to central facilities (14,22). TP and TN discharges and, to a lesser extent, COD in the treated water were the major contributing factors to eutrophication (29). The high removal efficiency and outlet water quality in summer will maintain the concentration of eutrophication, P-depletion, and dissolved oxygen in the receiving media (5). According to a study by Gutierrez et al (73), the currency of the potential impacts related to the category of eutrophication is primarily through inadequate removal of nitrogen and phosphorus in these systems.

The removal of COD is responsible for the possible human and environmental toxicity effects during the operation phase of NWTS. Chemical consumption and heavy metal removal increase the human toxicity effect (up to 90% of the overall impact), which is reduced owing to NWTSs' chemical-free and high heavy metal removal. Constructed wetlands help reduce the environmental impact, particularly the high treatment efficiency and low chemical and electricity consumption (14). In the LCA study (5) conducted in a facility that integrates central wastewater with constructed wetlands, the global warming effect was negative due to methane formation. However, it has a low environmental impact because of its high removal efficiency, water reuse, and photo treatment.

Commercial software is dependable and crucial for speed in LCA evaluations. According to a study by Gallego, the lack of commercial software in LCA studies allowed the researchers to only consider certain aspects of analyses, which slowed down the process. Consequently, developing free and open-access versions will contribute positively to increasing these studies in the coming years (38).

In a study by Saad et al (48) investigating the electricity consumption of large-scale treatment plants in Turkey and the potential effects of global warming, conventional treatment plant power consumption of 0.39 to 0.82 kWh/m^3 was determined, and it was reported that 60% of the electricity consumption of the plants are caused by the consumption of the pumps (48,74). In another LCA study, while the average energy consumption of wastewater treatment plants in developing and developed countries was 0.44 and 0.52 kWh/m^3, the global warming effect was 0.56 and 0.4 kg CO_2/m^3 (38). Three facilities conducted an energy-free treatment process when the global warming values of the investigated NWTS were examined. Comparatively, the level of electric consumption in traditional wastewater treatment facilities was under 50% on average (Figure 7).

Conclusion

The environmental impact of nitrogen and phosphorus is proposed to be reduced by lowering the content of nutrients in the effluent. Therefore, it is necessary to improve the removal efficiency of high-impact values, particularly nitrogen and phosphorus. The pathogen and/or coliform readings at these facilities should be investigated in the context of public health. Pumps from the systems were taken into account when calculating electrical loads. By converting the inlet architecture of these three NWTSs to gravity flow systems, an electrical load can be removed. In addition to examining the efficiency classes of the pumps, switching to high-energy efficiency class (IE 3 or IE 4) pumps can save energy expenses by up to 15%.

Although the aforementioned NWTSs satisfy the legal discharge requirements for the receiving environment, because the receiving environment is a "sensitive region," it may be acceptable to implement stricter treatment methods than those required by the regulations. LCA was used to investigate the environmental effects of NWTSs, whose effects were not taken into consideration during the construction phase and were instead evaluated by operating parameters as inputs and outputs. According to the effluent wastewater quality, the effects of the facilities on energy use, COD, nitrogen, and phosphorus effects on the environment, and climate change were assessed. Deydinler, Yenice, and Pinar had the highest removal efficiency among the NWTSs with the highest environmental effects in terms of nitrogen, phosphorus, and COD (induced by significant COD contamination from livestock activities in the area). Only one of the ten NWTSs assessed for freshwater eutrophication generated significantly more eutrophication than the other nine NWTSs.

The effectiveness of NWTS therapy must be evaluated using the LCA analysis approach to assess the consequences on the environment and human health. As a contribution to Sustainable Development Goal Part 11, "Sustainable Cities and Communities," this research focused on the effectiveness and LCA for NTWSs. Low energy usage and treatment effectiveness were assessed for NWTSs. In future research, it would be beneficial to combine the findings of these facilities' carbon footprint with LCA studies and their contribution to the 11th SDGs in addition to evaluating their impact on the countries' carbon-neutral ambitions.

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Authors' contribution

Conceptualization: Berrak Erol Nalbur.
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Formal analysis: Berrak Erol Nalbur.
Funding acquisition: Berrak Erol Nalbur.
Investigation: Özcan Yavaş.
Methodology: Özcan Yavaş.
Project administration: Berrak Erol Nalbur.
Resources: Berrak Erol Nalbur.
Software: Özcan Yavaş.
Supervision: Berrak Erol Nalbur.
Validation: Berrak Erol Nalbur.
Visualization: Özcan Yavaş.
Writing-orginal draft: Özcan Yavaş, Berrak Erol Nalbur.
Writing-review & editing: Özcan Yavaş, Berrak Erol Nalbur.

Competing interests

The author declares that there are no competing interests.

Ethical issues

The authors hereby certify that all data collected during the study are as stated in the manuscript, and no data from the study have been or will be published separately elsewhere.

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