Environmental Performance Assessment of Decentralized Wastewater Treatment System in Jordan Using Life Cycle Analysis

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***Abstract*—This research utilized Life Cycle Analysis (LCA) within SimaPro 9 software to evaluate the potential environmental burdens: global warming, eutrophication, acidification, and ozone layer depletion of three Decentralized Wastewater Treatment Systems (DWWTS) in Jordan over the entire period of its life cycle of construction and operation phases. The obtained laboratory test results showed that Feynan (M1) has the best performance regarding treatment efficiency, where the treated effluent parameters TN, TP, COD, and BOD were the lowest compared to Jerash (M2) and SMART (M3). On the other hand, the overall outcomes show that M3 and M2 are approximately 25% and 50%, respectively, compared to M1 contribution in burdens. Construction of wetlands has the highest contribution to most of the environmental burdens of the three plants. It was found that cement production is the key factor causing environmental burdens resulting from the construction of these plants. Whereas concrete blocks, reinforcing steel, and PVC pipes have less contribution. LCA is approved as a supportive investigation of the environmental burdens of such plants that guide decision-makers in developing new strategies to achieve sustainability.**

***Index Terms*—Decentralized Wastewater Treatment Systems (DWWTS), Life Cycle Analysis (LCA), Jordan, SimaPro**

I. Introduction

Globally, in 2017, it was claimed that 70% of the world's population is served by basic wastewater treatment utilities, while 45% of people have safely managed sanitation coverage. It is thought that at least 10% of people consume crops irrigated by wastewater. In addition, about 1 million people lost their lives due to the pollution of fresh water with wastewater. Urban areas are more covered with sanitation services than rural areas; 82% of people in urban areas are served by sanitation, while 51% of people in rural areas can be availed by sanitation. On the economic side, it was estimated that for every 1 US $ paid in sanitation services development, there are about 5.5 US $ returned in low health costs [1–3]. In Jordan, 63% of the inhabitants are supplied by sanitation utilities. There are 33 centralized wastewater treatment plants installed all over the country; agricultural usage exceeds 90% of treated wastewater [3]. Last decade, refugees' flux has increased the water demand, in addition, climate models expect up to a 60% reduction of overall rainfall in Jordan by the end of the twenty-first century. This situation highlighted the necessity of a treatment system that reduces the burden on the central sanitation system but is also less costly [4, 5].

Jordan National Water Strategy 2016-2025 was proposed corresponding to necessity of managing wastewater and recycling out of the traditional sanitation system in which Decentralized Wastewater Management Policy was developed. This Policy is a guide for decision- makers to planning, implementing, and operating decentralized wastewater management infrastructure. The policy was formulated taking in consideration regulations, standards, and inter-sectorial responsibilities while maintaining the imperative of the protection of public health and water resources for a successful implementation and sustainable operation [4].

Decentralized Wastewater Treatment System (DWWTS) is a smart technique to deal with the current situation in Jordan. The net environmental benefit of the DWWTS can be only perceived by taking into account entire life cycle phases of the wastewater treatment system phases.

The current research utilized Life Cycle Analysis (LCA) method to obtain an integrated assessment aims to investigate the environmental efficiency of the DWWTS in Jordan. It covers the stage of construction of the treatment units in addition to the stage of operation regarding to that the main contributor of environmental impacts are the material and resource used in building of the units. The specific objectives of the research:

- To develop a life cycle inventory (material consumption and environmental releases) of small-scale DWWTS.
- To define the environmental hotspots for small-scale decentralized wastewater treatment system (DWWTS) based on its environmental performance.
- To assess and compare the environmental performance of the DWWTS using LCA tool.

II. Literature Review

A. Centralized versus Decentralized Wastewater Management

A decentralized system is defined as an onsite wastewater treatment system which is used to weed out and treat wastewater independently of central plant. It disposes of small quantities of wastewater found in clusters, generally consisting of a single or cluster of households and businesses located nearby [6]. Centralized systems' benefit is uniformity, ensuring they address the water demand and quality criteria in a large community. They can be controlled and subject to a

Manuscript received January 15, 2023; revised March 29, 2023; accepted August 11, 2023.
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doi: 10.18178/ijesd.2023.14.6.1457

certain extent of inertia in financial, organizational, system operations, and technical matters [7]. Decentralized wastewater management has been used commonly in low-income countries since it is more cost-efficient than centralized systems, in addition to compatibility with low-density communities and varying site conditions. As pertaining to the participation of local human resources, centralized systems are located far from populated areas and hence, require less public involvement and awareness [8]. Besides the environmental advantages of decentralized management, like curtailment of the risk of drought and reducing the impacts on public health, it also raises the ultimate reuse of wastewater depending on varying factors related to community and site settings. Efficient utilization of DWWTS consolidates the resumption of treated wastewater within the watershed of origin [9, 10].

B. Design Approaches of DWWTS

Typical DWWTS can provide primary, secondary and tertiary treatment. Primary treatment (e.g., settlers & septic tanks or biodigesters), secondary treatment (e.g., anaerobic baffled reactors& anaerobic filters), secondary aerobic/facultative treatment (e.g., occurs horizontal or vertical constructed wetlands and gravel filters), also post-treatment which occurs in aerobic polishing ponds [11].

C. Assessment of DWWTS

The decentralized sanitation management plans should consider the economic, environmental, social, and cultural state in the target zone. Massoud *et al*. [12] defined the "Most Appropriate Technology" as the technology that is economically affordable, environmentally sustainable, and socially acceptable as shown in Fig. 1.

Lienhoop *et al*. [13] monetized the benefits of two decentralized treatment technologies associated with the environment, health, and irrigation in agriculture using the cost–benefit analysis (CBA) includes non-market benefits.

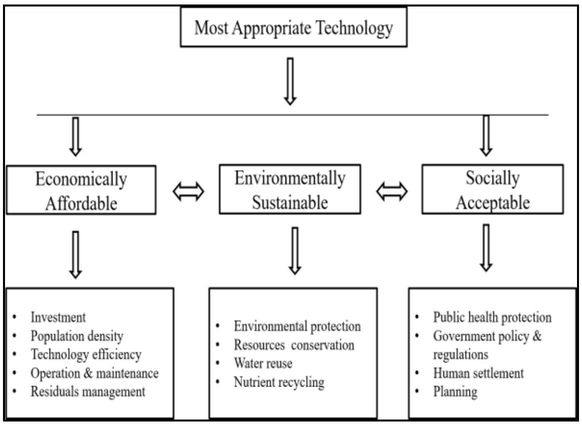


Fig. 1. Characteristics of the most appropriate technology [12].

Various methods have been applied to assess the overall environmental functioning of the system like BioWin® modeling, SPSS® software, and DRASTIC Model. for example, BioWin® modeling was utilized to compare two different types of DWWTS, MBR, and aerobic biofiltration, the energy requirement for MBR system was noticeably higher, also produced carbon dioxide equivalent value due to the communal septic tanks associated with aerobic bio-filtration system was close to that of the MBR. Electrical energy consumption inputs significantly minimize the overall GHG footprints for the onsite treatment systems [14–16].

In general, the social implications of decentralization processes are repeatedly belittled compared to the economic and environmental ones [17]. In decentralization conditions, regardless of the authorization and implementing procedure, the end user is responsible for its management: this is the most critical point to consider [18].

D. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a quantifiable method that estimates the environmental effects of a system over the entire period of its life cycle [19, 20]. LCA methodology is currently seen as an adequate framework to assess the sustainability of a product or process [21]. Fig. 2 illustrates the phases of LCA according to ISO 14040:2006.

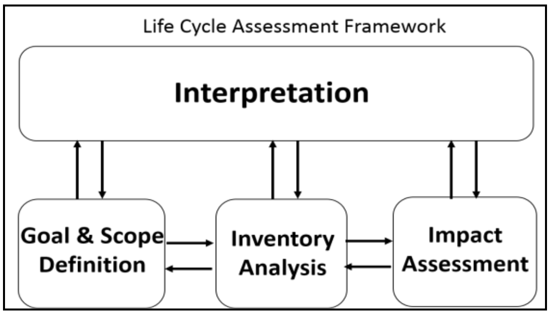


Fig. 2. LCA main steps, according to ISO 14040:2006.

LCA has been applied to various products and systems in different fields, the beginning was to estimate the environmental influence of beverage packaging systems in the last of the 1960s and the start of the 1970s [22]. Nowadays, LCA has been approved to evaluate any product e.g., it was found that concrete occupies about 65% of overall energy consumption associated with the primary construction materials used to build an individual house; concrete and mortar are the significant contributors to total CO_2 emissions with 99% [23]. Machado *et al*. [24] used the LCA tool within the software SimaPro7 to compare three onsite DWWTS regarding their environmental burdens.

III. Research DWWT Plants Background

A Project in the Lower Jordan Rift Valley entitled SMART (Sustainable Management of Available Water Resources with Innovative Technologies) was funded by German Federal Ministry of Education and Research. The project was constructed in (2006–2014) and implemented by UFZ, a German research center, in cooperation with the Jordan Ministry of Water and Irrigation and Al-Balqa' Applied University. The selected DWWT plant is with treatment capacity of 2 m^3/day.

In the year 2015, USAID sponsored a small onsite sanitation in partner with the Royal Society for Conservation of Nature (RSCN). The DWWT plant at Jerash governorate was a part within a project titled as "Expanding Access to Sanitation for Unsewered Communities in Middle East and North Africa Countries". The plant contains two treatment units with a capacity of 1 m^3/day.

Feynan Ecolodge DWWT plant is a cooperative project located at Al-Tafilah governorate, Dana Biosphere Reserve specifically. The project known as Climate Change Adaption (ACC-project) was carried out by BORDA and GIZ in 2017. It was implemented in corporation with (RSCN), with treatment capacity up to 10 m^3/day.

The locations of these DWWT plants (modules) used in this research are shown in Fig. 3 with respect to the centralized wastewater treatment plants in Jordan.

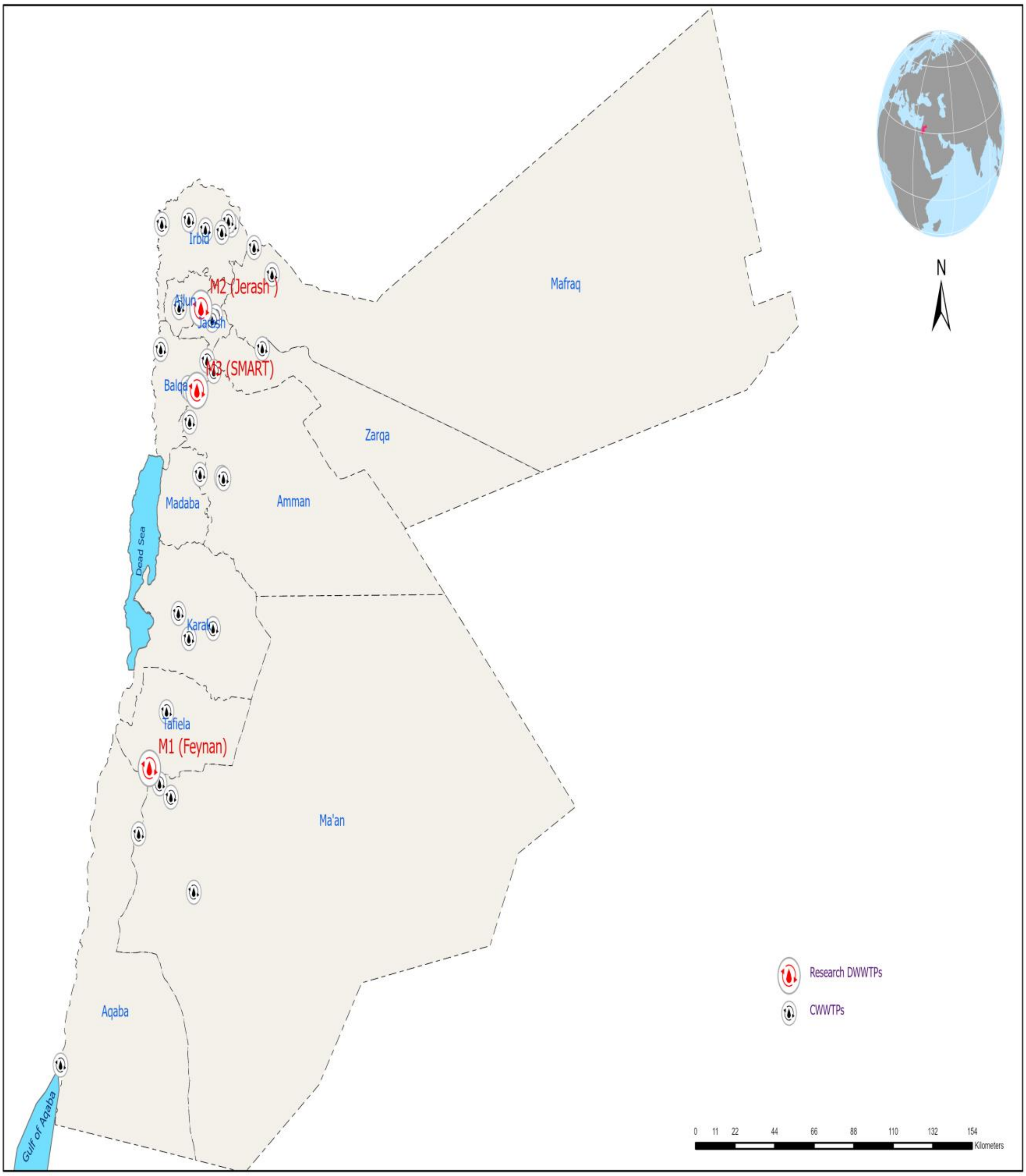


Fig. 3. The locations of research DWWT plants (modules) and centralized wastewater treatment plants in Jordan.

IV. MATERIALS AND METHOD

A. Goal and Scope

The goal of the research is to compare the three DWWTS modules in terms of their environmental performance. Feynan (M1) consists of a biogas settler, anaerobic baffled reactor (ABR), and vertical flow constructed wetland (VFCW). Jerash Plant (M2) and SMART Project contain the same units: the septic tank and vertical flow constructed wetland. The scope describes the most important methodological choices, assumptions, and limitations of the study [25]; for this research, the scope is limited to the construction and operational stages. The computer-based software 'SimaPro' is used in this research. A functional unit is a quantified description of the performance of the product systems for use as a reference unit [26]. The functional units assumed for this research are kg/pe/year for the construction phase, while the performance during the operation phase is expressed by mg/L. The system boundary was considered, as presented in Fig. 4.

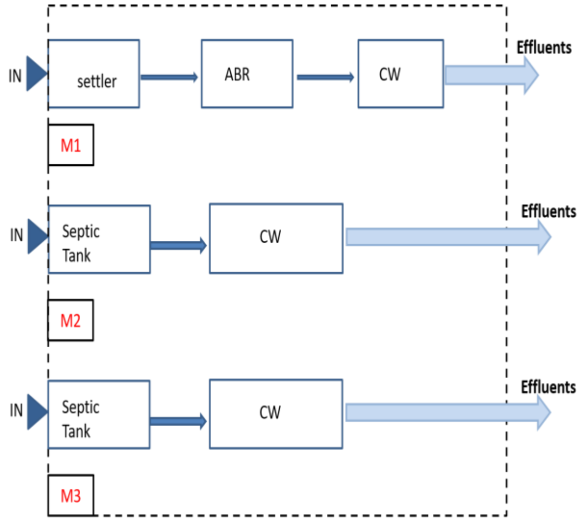


Fig. 4. System boundary for this research.

B. Inventory

In this step of LCA, the environment input and outputs were quantified and calculated. MS Excel was used to prepare the inventory table. Removal efficiencies for BOD, COD, TN, and TP were estimated. Whereas construction materials (clay brick, concrete block, cement, gravel, reinforcement steel, sand, and plastic) were quantified in the selected functional unit (kg/pe/year). The design period for plants was assumed as 20 years. SimaPro contains details of the input and output database and provides the inventory result by interpreting the process structure [25]. The main purpose of this phase is to determine the processes and assemblies of the system.

C. Impact Assessment

In this research (CML-IA baseline) method and (EU25+3, 2000) normalization set have been selected to evaluate the environmental impacts. The results of the inventory phase are classified and characterized into the impact categories chosen for the present research Acidification Potential (AP), Global Warming Potential (GWP) or the Greenhouse effect, Ozone Layer Depletion Potential (ODP), and Eutrophication Potential (AP) to the relevancy of the research goal. Table I includes the impacts investigated for this research and the reference emissions. The last step of this phase is normalization, which illustrates a result of an impact category indicator whether it is a relatively high or relatively low value compared to a reference.

TABLE I: THE IMPACTS INVESTIGATED FOR THIS RESEARCH [27]

Category	**Flows**	**Characterization Factor**	**Reference**
Global Warming	CO_2, CH_4, NO_2, CFC	Global warming potential	CO_2
Ozone depletion	CFC, HFC, Halons	Ozone depleting potential	CFC-11
Eutrophication	PO_4, NO, NO_2, NH_4	Eutrophication potential	PO_4^{3-}
Acidification	SO_x, NO_x, HCl, NH_4	Acidification potential	SO_2

V. RESULTS AND DISCUSSION

The performance of each treatment system during the operation phase was analyzed depending on effluent compositions of Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Nitrogen (TN), and Total Phosphorous (TP) in mg/L based on test results for all treatment modules, (see Table II). The removal efficiency of the tested contaminant for each unit is presented in Table III-A, B & C. The findings show high net performance according to the Jordanian standard (JS893/2021 - Class C), category of field crops, industrial crops, and forest trees. The contribution of each M1, M2, and M3 treatment unit to the selected burden is presented in Fig. 5. In general, results show that the unit with larger construction in each module has a higher contribution.

TABLE II: THE PROCESS PARAMETER FOR ALL DWWTS MODULES

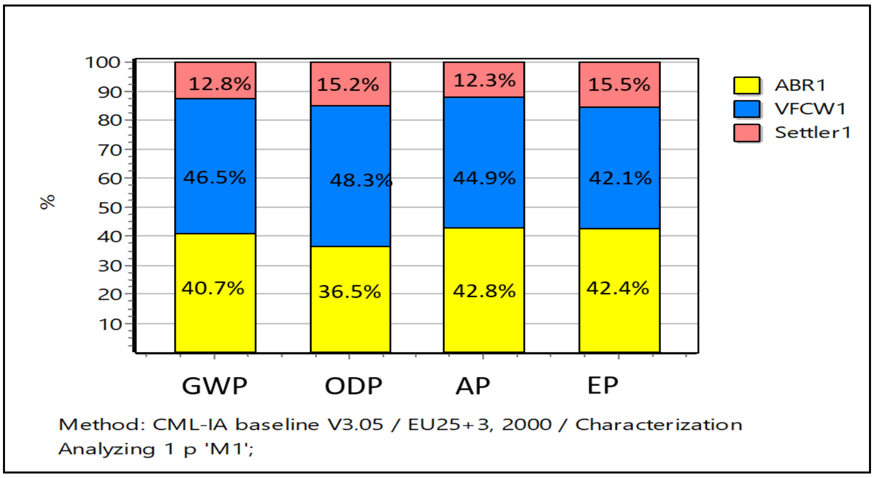
SN	Parameters	M1 Effluent quality (mg/l)	M2 Effluent quality (mg/l)	M3 Effluent quality (mg/l)	*JS (893/2021) (mg/l)
1	TN	22	72.12	79	100
2	TP	12.4	12.4	12.4	30
3	BOD	3	22.6	21.9	300
4	COD	19	86.2	105.2	500

* Jordanian Standard for reclaimed domestic wastewater, No.893/2021

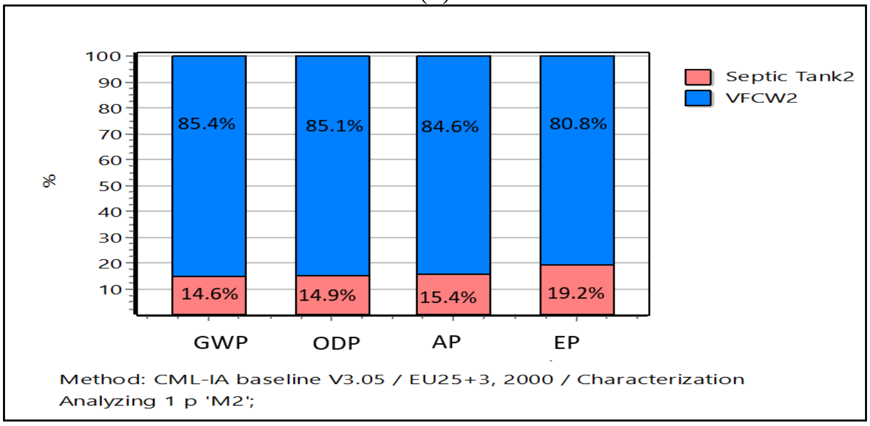
TABLE III: PERFORMANCE OF DWWTS MODULES

A. Performance of M1									
Parameter	Settler			ABR			VFCW		
	Influent	Removal %	Effluent	Influent	Removal %	Effluent	Influent	Removal %	Effluent
N (mg/l)	158.9	0%	158.9	158.9	0	158.9	158.9	86%	22
P(mg/l)	24	0%	24	24	0	24	24	48%	12.4
BOD (mg/l)	-	-	414	414	48%	217	217	99%	3
COD (mg/l)	-	-	908	908	50%	454	454	96%	19
B. Performance of M2									
	Septic Tank			VFCW					
	Influent	Removal %	Effluent	Influent	Removal %	Effluent			

N (mg/l)	213.9	0%	213.9	213.9	66%	72.12
P(mg/l)	24	0%	24	24	48%	12.4
BOD (mg/l)	741.3	61%	287	287	92%	22.6
COD (mg/l)	1905.3	62%	715.33	715.33	88%	86.2
C. Performance of M3						
	Septic Tank			VFCW		
	Influent	Removal %	Effluent	Influent	Removal %	Effluent
N (mg/l)	141.9	27%	103.4	103.4	24%	79
P(mg/l)	24	0%	24	24	48%	12.4
BOD (mg/l)	587.7	39%	356.2	356.2	94%	21.9
COD (mg/l)	878.3	27%	641.2	641.2	84%	105.2



(A)



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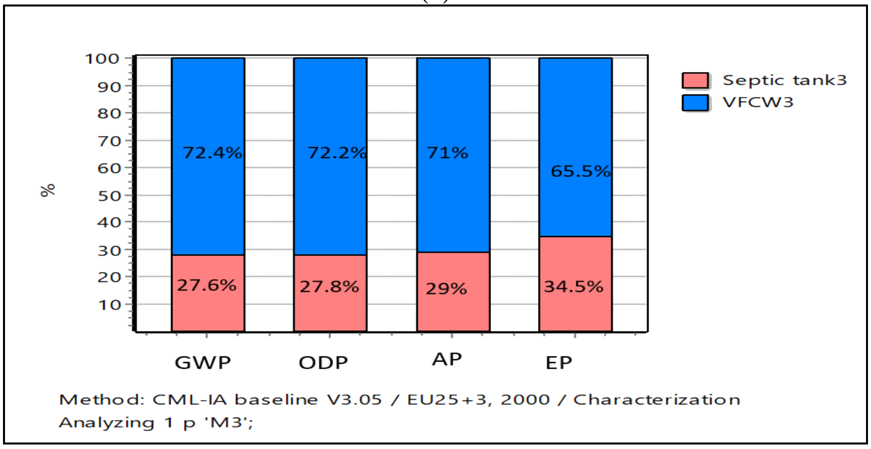

(C)

Fig. 5. Contribution of each treatment unit to the environmental burdens: (A) DWWTS module 1 (M1), (B) DWWTS module 2 (M2), (C) DWWTS module 3 (M3).

M1: based on Table III-A, COD and BOD values in the influent of the settler haven not been considered; referring to the design report, sampling and analyzing are not recommended for biogas settler since characteristics of sewage at the inlet of the settler are widely varying through seasons [28]. ABR showed moderate removal efficiency to BOD and COD, up to 48% and 50%, respectively. This unit is based on anaerobic treatment. The efficiency during winter will be much less than during the summer period. This module has the best performance in regard to treatment. As shown in Fig. 5(A), VFCW is responsible for all impacts followed by the ABR unit, whereas the septic tank has the least contribution. M1 has the largest construction materials content in specific cement and blocks; globally, the production of these only two materials is responsible for 7–8% of overall CO_2 emissions since it consumes a large amount of energy [29].

M2: Table III-B shows that the septic tank's performance has not yet reached a steady state, though organic matter removal efficiency exceeded 60%. According to Metcalf & Eddy (2003), aerobic treatment requires 2–14 weeks to build up the biomass, which is essential for treatment. As shown in Fig. 5(B), VFCW is a much higher contributor to all impacts than the septic tank.

M3: The septic tank has average removal efficiencies for COD and BOD of 27% and 39%, respectively (see Table III-C), which are below the expected limit of 50%. Test results show a reduction in TN content since the S unit is followed by a vertical filter that promotes aerobic processes such as organic matter decomposition and nitrification (conversion of ammonium (NH^{4+}) to nitrate (NO^{3-}), then the organic matter strip out the oxygen leaving nitrogen in the gaseous state above water.

The characterized values for studied impacts are presented in Table IV, whereas Table V compares normalized values. While Fig. 6 compares the three modules with respect to their impacts.

TABLE IV: COMPARISON OF IMPACT CATEGORIES OF M1, M2, M3

Impact Category	M1	M2	M3
AP (kg SO_2 equivalent/pe/y)	0.142	0.0725	0.0333
EP (kg phosphate equivalent /pe/y)	0.0201	0.0101	0.00481
GWP (kg CO_2 equivalent /pe/y)	48.5	25.5	11.6
ODP (kg CFC equivalent /pe/y)	2.12E-06	1.16E-06	5.3E-07

TABLE V: NORMALIZED VALUE FOR POTENTIAL IMPACTS FOR M1, M2, M3

Impact Category	Normalized value (M1)	Normalized value (M2)	Normalized value (M3)
AP	8.43E-12	4.31E-12	1.98E-12
EP	1.08E-12	5.44E-13	2.6E-13
GWP	9.32E-12	4.89E-12	2.23E-12
ODP	2.08E-13	1.14E-13	5.2E-14

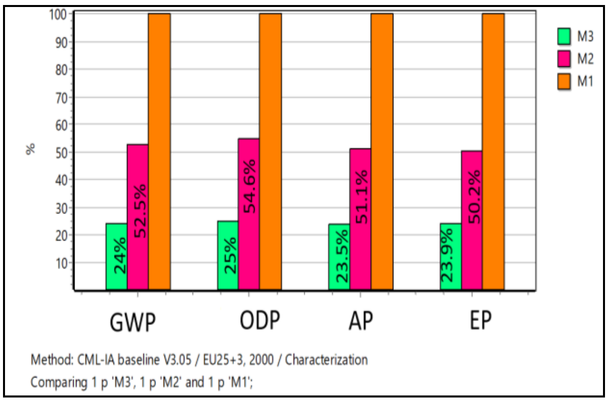

Fig. 6. Comparison of the environmental performance of treatment modules M1, M2, and M3.

Global Warming Potential (GWP 100): The GWP is identified for each module for a time horizon of 100 years. Referring to Table V, the M3 has the best GWP performance (2.23E-12) and contributed 11.6 kg CO_2 as shown in Table IV. Network analysis in SimaPro estimated that cement is responsible for about 70% or more of GWP.

Ozone Layer Depletion (ODP): ODP indicates the phenomenon of decreasing ozone density through the thinning of the stratospheric ozone layer. The standard substance for ODP is CFCs [30]. M3 is the best option, with a normalized value of 5.2E-14. In the current research, M1 represents the highest contributor to ODP, 2.12E-6 kg CFC-11 equivalent/pe/y, and M3 is 25% compared to M1. Cement contributes up to 82.9% of ODP.

Eutrophication Potential (EP): EP occurs when inland waters are heavily loaded with excess nutrients due to chemical fertilizers or discharged wastewater, triggering rapid algal growth and red tides. The main substances emitted in the concrete production process. The standard substance for EP is PO_4^{3-} [31]. Based on Fig. 5, M3 also has the best EP performance; it is 23.9% of the EP of M1.

Acidification Potential (AP): AP impact arises from acidifying gases like SO_x, NO_x, and NH_3 into the atmosphere. The emission of kg SO_2 as equivalent is an indicator of this environmental burden. M3 is considered less impact. The AP for M3 was 0.0333 kg SO_2 equivalent/pe/y, which 23.9% of M1. Network analysis reveals that 70% of the emission of SO_2 in the entire life cycle of decentralized wastewater treatment plants is mostly during the concrete blocks and cement production.

Sensitivity analysis was applied to check how much the change in daily flow does influence the environmental impacts (GWP, ODP, AP, and EP). The daily flow was increased from 6 m^3/day (case 1) to 10 m^3/day (case 2) in M1, which means that (pe) increased from 70 to 117, and the functional unit was the same that adopted for this research (kg/pe/y). Table VI shows the normalization value for each case, all impact categories have been reduced by 40% percent. For M2 and M3, the flow was increased to 1.5 and 2.4 m^3/day, respectively. Normalization values were reduced by 33% and 17% for M2 and M3, respectively. While removing the ABR unit from M1 decreased the potential impacts: of global warming, ozone layer depletion, acidification, and eutrophication by 41%, 37%, 43%, and 42%, respectively.

TABLE VI: COMPARING CASE 1 VS. CASE 2 FOR M1

Impact Category	Case 1, flow= 6 m^3/day, pe=70	Case 2, flow= 10 m^3/day, pe=117
AP	8.43E-12	5.06E-12
EP	1.08E-12	6.49E-13
GWP	9.32E-12	5.58E-12
ODP	2.08E-13	1.24E-13

VI. CONCLUSIONS

In the current research, LCA tool has been applied for the environmental assessment of DWWTS. The LCA is a helpful tool to analyze the environmental impacts of such projects that are essential to be a part of the decision-making process toward sustainability. The research results show that M1 is the best for operation stage performance regarding processing wastewater.

On the other hand, it was found that M3 is the best module on the overall impact analysis during the different life cycle phases of the modules. The impact of ABR, S, and VFCW are also found to be different from each other. VFCW has the highest environmental impact. It is also noticed that each unit requires a different quantity of materials for installation. It means that the environmental burdens of the units are also different. It can be said that more treatment units can achieve better quality effluent, at the same time, will increase the quantities of material used in construction, which has a more considerable influence; accordingly, the key to mitigating burdens is controlling construction materials.

The following recommendations are suggested based on the current research:

- The life cycle assessment research is recommended to compare the environmental performance of the small decentralized wastewater systems and the commonly used centralized systems in developing countries.
- It is recommended to investigate other probable emissions during the operation of the units, allowing more accurate evaluation.
- Such projects require governmental sponsorship to expand utilization as an alternative to cesspits in rural areas with higher population coverage, where the general income is limited. In contrast, urban areas (better material situation) are connected to centralized plants.
- Knowing that onsite treatment techniques are more feasible when the system serves more people, further research is needed to evaluate these decentralized systems economically.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hiba Nofal: conceptualization, data collection and analysis, investigation, visualization, writing–original draft preparation. Ramia Al-Ajarmeh: conceptualization, supervision, visualization, writing–review and editing.

Acknowledgments

We acknowledge the required research data by (1) Al-Balqa' Applied University (BAU) / International Research Center for Water, Environment & Energy represented by Dr. Amal Al-Abbadi and Eng. Mohammed Jadallah (2) GIZ JO represented by Mr. Trevor Surridg/ Project Manager of Decentralized Wastewater Management for Adaptation to Climate Change in Jordan (ACC Project), Mr. Hisham Asalamat and Mr. Bisher Nabulsi, the Operations Director at EcoHotels (3) Dr. Almoayied Assayed/ Water Studies Division Center for Water and Environment/ Royal Scientific Society, Jordan.

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