Multi-criteria Assessment of Onsite Packaged Wastewater Treatment Systems

Mohd Elmuntasir Ahmed, A. Al-Matouq, M. Khajah, H. Abdullah, and F. Al-Ajeel

Abstract—Onsite wastewater treatment systems and small scale packaged wastewater treatment plants have been used on a large scale in developing and developed countries where centralized sewerage facilities are not feasible. Generally, onsite systems continuously work under significant variations in both quantity and quality of the influent wastewater. Therefore, their suitability needs to be assessed before installation and operation to ensure their suitability and sustainability. This paper aims to define a set of context-specific criteria to assist in selecting the best onsite wastewater treatment system and to break down these criteria into measurable parameters. Furthermore, the developed multi-criteria assessment tool was validated using the results of the performance monitoring of a selected wastewater treatment system. This work is important since the selection of onsite systems, in many cases, is done based on declared performance by the supplier and the costs involved.

Index Terms—Multi-criteria, onsite wastewater treatment, packaged wastewater treatment systems, wastewater reuse, wastewater treatment.

I. Introduction

Onsite sanitation facilities have been used on a large scale in developing and developed countries where centralized sewerage facilities are not feasible. All over the world, about 2.7 billion people depend on onsite sanitation facilities [1]. Rapid urbanization in low and lower-middle-income countries, especially in small towns where the existing infrastructure and management capacity are usually limited, accentuates the challenge of providing a fully functioning wastewater treatment service [2]. The lack of financial resources to operate and maintain small Wastewater Treatment Plants (WWTPs) in low and lower-middle-income countries has been identified as a critical reason for the failure of these systems, alongside inappropriate design or selection of technology, poor operation and maintenance, lack of technical expertise, and lack of monitoring [3].

Moreover, in many countries, unplanned growth, often without a proper infrastructure for wastewater treatment, is taking place [4]. Where efforts have been made to treat wastewater in small towns, it is typically achieved by establishing small-scale wastewater treatment plants [5].

Among the various individual (onsite) solutions, one of the

best options in terms of risks to health and environment, technologies and methods of operation and socio-cultural acceptance (not so much in terms of economic and financial issues) are the so-called packaged or onsite wastewater treatment plants. These systems are designed as real treatment plants but on a smaller scale. Provided that best practices for operation and maintenance are followed, they are a potential solution to wastewater treatment and, in some cases, also to nutrient management [6], [7].

Given the lack of freshwater availability globally and in Arid countries particularly, it has become necessary to use onsite treatment systems to treat wastewater and reuse the effluents. As climate change poses serious threats to global water security [8], onsite wastewater treatment systems could provide an adaptation and mitigation to climate change in hard-hit countries by providing effluents of suitable quality for reuse [9]. Also, it has been pointed out that environmental pollution, water scarcity, population growth, innovation, and technological developments encourage rethinking the current approach to urban water management [10], [11]. Treated wastewater is a valuable but non-traditional resource that could help to compensate for the withdrawal of freshwater from agriculture and provides significant opportunities to fill the water availability gap [12], [13].

Generally, onsite systems continuously work under large variations in both quantity and quality of the influent wastewater. Therefore, their suitability needs to be assessed before installation and operation to ensure their suitability and sustainability. Tchobanoglous *et al.* [14] provided a list of 21 criteria to evaluate a wastewater treatment plant's performance. These criteria need to be broken down into measurable parameters to enable evaluation. Also, Bradley *et al.* [15] further expanded these criteria to include sustainability of these treatment systems, including social, economic, and environmental criteria and provided evaluation for two types of treatment systems.

Several methodologies and tools that support the selection of small scale wastewater treatment technologies have been developed. These include, for example, a tool for combining environmental and economic aspects when designing WWTPs for small communities [16], a target plot to evaluate the sustainability of decentralized domestic wastewater treatment technologies [17], and a practical tool to assess the sustainability of small wastewater treatment systems in low and lower-middle-income countries [5].

Most of these assessment tools examine specific dimensions such as sustainability and life cycle assessment. Therefore, there is a need to develop tools for selecting onsite systems and assessing their long-term performance in meeting their installation objectives. As such, this paper aims to define a set of context-specific criteria to assist in selecting

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the best onsite wastewater treatment system and break down these criteria into measurable parameters. Furthermore, the multi-criteria assessment tool will be validated using the selected wastewater treatment system performance results. This work is important since the selection of onsite systems, in many cases, is done based on declared performance by the supplier and the costs involved.

II. METHODOLOGY

The aim of developing the Multi-Criteria Assessment (MCA) tool is to select the best system available in the market and assess the system's performance after installation and operation.

The criteria were developed based on performance aspects, energy consumption, ease of operation, and flexibility of handling variable quality and flow, among others. The full list has been detailed based on previous studies while maintaining the context insight. Once the full list of criteria was developed, for each criterion, a suitable list of parameters was selected, weight (importance) assigned, and then the MCA was evaluated based on the total score. The data for this step were obtained from the suppliers of onsite systems available in Kuwait.

For the long term performance evaluation and MCA validation, the onsite system was installed, parameters monitored, and the performance was evaluated.

For wastewater effluent quality, parameters included in Kuwait EPA (KEPA) guidelines [18] were monitored and analyzed according to APHA [19]. The monitoring plan is shown in Table I.

TABLE I: MONITORING PLAN

Period and expected dates	Sampling frequency	parameters	Other field parameters
First two weeks	daily	temperature, pH, BOD, COD, TN, TP, and VSS	Flow, electrical consumption, sludge volume
Month and a half (end of April 2020)	weekly	KEPA Table 15 nitrite, nitrate, and VSS	Flow, electrical consumption, sludge volume
1 month (end of May)	biweekly	KEPA Table 15 nitrite, nitrate, and VSS	Flow, electrical consumption, sludge volume
3 month (end of August)	monthly	KEPA Table 15 nitrite, nitrate, and VSS	Flow, electrical consumption, sludge volume

III. RESULTS AND DISCUSSION

A. Onsite Treatment Systems Requirements and Assessment

According to Wilderer and Schreff [20], the successful implementation of a decentralized system requires the following conditions:

1) Decentralized wastewater treatment systems must provide advanced wastewater treatment; they must be highly effective, robust, easy to operate, and low in costs.
2) Operation and control of the treatment systems must be accomplished by trained personnel.
3) Water is a valuable material, especially in water shortage

areas (such as arid and semi-arid countries).
4) It should be realized that wastewater generated in households, enterprises, and industrial plants has a different flow, concentration, and loading characteristics. Some of these characteristics may require sophisticated treatment processes.

Several techniques could be used separately or in combination in onsite wastewater treatment facilities [21]. Some techniques such as grit separation, sedimentation, air flotation, filtration micro-and ultrafiltration, and oil-water separation are mainly used in combination with other technologies as a part of the treatment scheme. Physio-chemical treatment techniques such as coagulation/ precipitation/ sedimentation/ filtration, crystallization, chemical and wet air oxidation, supercritical water oxidation, chemical reduction, hydrolysis, nano-filtration, reverse osmosis, adsorption, ion exchange, extraction, distillation/ rectification, evaporation, stripping and incineration are primarily used for non-biodegradable wastewaters, inorganic or hardly biodegradable organic contaminants. At the same time, biological treatment techniques, including anaerobic/aerobic processes, nitrification/denitrification, and central or decentralized biological treatments, are considered for biodegradable wastewater [22].

Some of the attributes of onsite wastewater systems which are not directly efficiency-related are energy source (electric versus non-electric/renewable), noise, odor, and size [23]. Additionally, capital and operational costs are important factors since the scale factor of centralized versus decentralized is compromising the choice. Costs of land, access, electricity and site civil works necessitate design consideration, and hence packaged systems need to be carefully designed [24]. Notably, a successful packaged wastewater treatment system shall produce effluent that meets treatment targets, is capable of handling flow and load variations, easy to operate, has a simple design, has low maintenance costs, has insignificant aesthetic disruption, has low investment cost, small area requirement (footprint), and shall have long life and life cycle impacts [23].

In light of the preceding discussion, criteria were listed, and parameters were carefully integrated in line with Tchobanoglous *et al.* [14] list of performance criteria (Table II).

One of the main criteria which was not included was capital investment. The reason for not including capital investment in the MCA was that it might not reflect the actual cost of the plant since prices, tariffs, and taxes, vary depending on the origin of the product and, therefore, could not be used as a criterion for comparison of different systems. Additionally, the objective of the MCA was to evaluate the performance rather than the cost; for this reason, operation and maintenance costs were listed among the criteria.

TABLE II: CRITERIA FOR EVALUATING AND SELECTING ONSITE WASTEWATER TREATMENT SYSTEM

No.	Criteria	Parameters
1.	Process applicability	Yes, No.
2.	Applicable flow range	High flow or low flow (L/day – m3/day - L/hr – m3/hr)
3.	Applicable flow variation	L/day – m3/day - L/hr – m3/hr
4.	Influent wastewater characteristics	Temperature, conductivity, pH, DO, BOD, COD, (TOC), (TS), (TSS), TDS, NO2, NO3, NH3, N, P, K, CaCO3 alkalinity,

5.	Inhibiting and unaffected constituents	grease, heavy metals (Hg, Zn, Cu, Fe, Ni, Cr, As, Cd, Pb, Cn, As, B), total coliform, and fecal coliform. Inhibiting factors: pH, N, P, high concentration of salts, Magnesium, Calcium, high concentrations of nutrients, BOD/COD ratio, metals. Unaffected constituents: Antibiotics, Hormones, pharmaceutical compounds.
6.	Climatic constraints	Rising temperatures, intense wet seasons, the production of greenhouse gases (carbon dioxide, methane, and nitrous)
7.	Reaction kinetics and reactor selection	pH, oxygen supply, yield coefficient, coefficient decay, maximum specific growth rate, saturation constant, volume of wastewater, influent and effluent quality.
8.	Performance	Effluent quality, COD removal, BOD removal, KEPA irrigation standards, durability.
9.	Treatment residuals	Coagulants residuals- Sludge Treated-can be used- Volume- sludge handling and transportation.
10.	Sludge processing	
11.	Environmental constraints	wind direction, suitability of hydrogeological condition, location, environmental policy commitment, KEPA requirements, Public health risks, failure to meet effluent quality standards.
12.	Chemical requirements	Kg/day- Kg/m3
13.	Energy requirements	kWh/m3
14.	Other resource requirements	Manpower, transportation.
15	Personnel requirements	Skills- experience- language-PPE – training
16.	Operating and maintenance requirements	Warranty- Spare parts availability - Required Chemicals- High energy- Clear Manual- Safety requirements- cost- Startup period.
17.	Ancillary processes	Yes, Ancillary processes can be added, such as Membranes, RO, and advanced oxidation.
18.	Reliability	System components- Life cycle- Maintenance- Durability
19.	Complexity	No of components- No of processes- Sensors- Automatic or manual - Relationships between components
20.	Compatibility	Effluent quality- accommodate the generated volume of wastewater.
21.	Land availability	m2

B. Packaged Wastewater Treatment Unit Survey

An initial survey of types of packaged small-scale wastewater treatment systems available in Kuwait and abroad was conducted, and their overall description is tabulated in Table III. Table III indicates that most systems are similar in their treatment technology, and their core is biological treatment. Some systems have sequencing batch reactors, some have aeration tanks, and some have biological filters. However, the most important element is the availability of offices in Kuwait and the ability to provide service and civil works required for installation and maintenance, as confirmed by Peter-Varbanets *et al.* [25]. Abdullah et al.

(2018) has addressed the effluent quality of two onsite systems in Kuwait, and they were composed of settling, aeration tank (biological treatment), secondary clarification, and UV disinfection. However, effluent quality in the two systems studied was not reliable [26]. UV disinfection is preferred to chlorination since it requires no chemicals to operate small-scale onsite systems. Conversely, biological treatment could be significantly enhanced by integrating attached growth processes [27]. In this regard, the best system configuration was identified as composed of settling, aerobic attached growth biological treatment, secondary clarification, secondary settling, sand filter (to improve effluent quality before UV), and UV disinfection.

It is important to note that since, at this stage, these systems were not evaluated under operation, the multi-criteria sheets were populated from the technical specifications submitted. In many instances, the specifications do not give information on some criteria.

The first candidate was selected for installation and operation based on this general wastewater systems' information. In the next section, the use of the multi-criteria assessment tool will be demonstrated based on the actual operation of this system.

TABLE III: LIST OF PACKAGED WASTEWATER TREATMENT UNITS COMPANIES IN KUWAIT AND UNIT DESCRIPTION

No.	Company Origin	Type of Treatment in sequence	Disinfection	Comments
1	Denmark	Buffer tank, Settling Tank, Biological Treatment, Clarification	UV Treatment	Have Office in Kuwait
2	China	Settling Tank, Biological Treatment with Plastic Packing And Micro Porous Aeration System, Clarification	Not provided	Installation and service need to be Procured Separately
3	Turkey	Sedimentation Tank, Equalization Tank, Biological Treatment, Sand Filter, Carbon Filter	Sodium Hypochlorite System	Installation and service need to be Procured Separately
4	USA	Bar Screen, Settling Tank (equalization), Sludge Storage Biological Treatment, Clarification	Chlorination	Installation and service need to be Procured Separately
5	USA	Sequencing Batch Reactor	Not provided	Could be used for Industrial Wastewater as well
6	UK	Settling Tank, Biological Treatment, Clarification Tank, Sludge Recycle,	Not Provided	Requires 3-to 12- Month Service
7	Emirates, India	Buffer Tank, Settling Tank, Biological Treatment, Clarification	UV Treatment	Have Office in Kuwait

C. Multi-criteria Assessment (MCA)

TABLE IV: PROCESS PERFORMANCE OVERVIEW

No.	Parameter	Symbol	Unit	limits	% meeting limits
1	pH	pH	-	6.5 - 8.5	100
2	BOD5	BOD5	mg/L	20	100
3	COD (Dichromate)	COD	mg/L	100	100
4	Dissolved Oxygen	DO	mg/L	>2	100
5	Chlorine Residual	Cl2	mg/L	0.5 - 1.0	0
6	Floatables	-	mg/L	NIL	100
7	Oil/grease	-	mg/L	5	100
8	Total Suspended Solids	TSS	mg/L	15	85
9	Total Dissolved Solids	TDS	mg/L	1500	100
10	Phosphate	PO4-P	mg/L	30	100
11	Ammonium	NH4+	mg/L	15	100
12	Total Kjeldahl Nitrogen	TKN	mg/L	35	33
13	Phenol	C6H6O	mg/L	1	100
14	Fluoride	F	mg/L	2	100
15	Sulfide	S	mg/L	0.1	100
16	Aluminum	Al	mg/L	5	50
17	Arsenic	As	mg/L	0.1	34
18	Barium	Ba	mg/L	2	0
19	Boron	B	mg/L	2	0
20	Cadmium	Cd	mg/L	0.01	35
21	Chromium	Cr	mg/L	0.15	0
22	Nickel	Ni	mg/L	0.2	0
23	Mercury	Hg	mg/L	0.001	70
24	Cobalt	Co	mg/L	0.2	77
25	Iron	Fe	mg/L	5	71
26	Antimony	Sb	mg/L	1	27
27	Copper	Cu	mg/L	0.2	0
28	Manganese	Mn	mg/L	0.2	0
29	Zinc	Zn	mg/L	2.0	0
30	Lead	Pb	mg/L	0.5	82
31	Petroleum Hydrocarbons	TPH	mg/L	5	100
32	Total Coliform	-	CFU/mL	500	79
33	Faecal Coliform	-	CFU/mL	50	84
34	Escherichia coli	-	CFU/mL	50	67
35	Faecal Streptococci	-	CFU/mL	50	100
36	Egg Parasites	-	-	Nil	100

The wastewater treatment unit was run on sewage from the wastewater storage tank serving the office buildings. The system was continuously operated under steady and non-steady hydraulic loading conditions 24 h a day for 6 months. The average removal efficiency of the wastewater treatment unit under the variable hydraulic loading conditions was satisfactory, despite challenges imposed by the COVID-19 pandemic and its associated impacts on wastewater quantity availability and variability, which was different from the initial survey results. The effluent (treated wastewater) did not meet Kuwait EPA standards for certain parameters due to a lack of wastewater, resulting in internal circulation. However, this was of minor significance. The sludge accumulation during the 6- mo monitoring period did not warrant its removal since the amount was insignificant. The overall unit performance is given in Table IV.

However, the results of this study demonstrate that for some parameters, the declared and the actual efficiency are not quite identical. This difference in performance is typical of all small scale packaged wastewater treatment technologies [28].

Few observations relating to the wastewater treatment unit may need to take into account the issues as follows:
1) Pump malfunction was encountered one time during the 6-mo monitoring period.
2) The capacity of the storage and irrigation system did not keep up with the quantity of the effluent.
3) The sand filter's performance in removing nutrients and metals was below the required standards.

Clearly, the MCA (Table II) is subjective because the assigned weights are assigned based on judgement; however, it could also be a flexibility advantage since the users get to prioritize their interests when comparing available options [15]. Upon assigning weights, the user is able to define needs and compare options, as reflected in the example in Table V. As demonstrated in Table V, the performance and operation and maintenance costs were given the highest weights in our situation and then followed by other parameters, such as energy and chemical requirements.

TABLE V: MCA FOR EVALUATING AND SELECTING UNIT OPERATIONS AND PROCESSES FOR WASTEWATER TREATMENT

No.	Criteria/Factors	Assigned Weight %	Estimated Score
1.	Process applicability	8	8
2.	Applicable flow range	5	5
3.	Applicable flow variation	5	5
4.	Influent wastewater characteristics	5	3
5.	Inhibiting and unaffected constituents	2	1
6.	Climatic constraints	2	2
7.	Reaction kinetics and reactor selection	2	2
8.	Performance	10	8
9.	Treatment residuals	5	5
10.	Sludge processing	5	5
11.	Environmental constraints	2	1
12.	Chemical requirements	8	8
13.	Energy requirements	8	8
14.	Other resource requirements	2	2
15.	Personnel requirements	2	1
16.	Operating and maintenance requirements	10	10
17.	Ancillary processes	2	2
18.	Reliability	5	4
19.	Complexity	2	2
20.	Compatibility	5	4
21.	Land availability	5	5
	Total value	100%	79%

The MCA findings suggest that a system could be selected to achieve the desired outcomes best. However, it should be appreciated that local conditions often limit the system design. Therefore, in practice, the flexibility of the design may be more limited than might be suggested here [29].

By and large, at this stage, the selected system has met the TOR requirement. However, further improvement in the future is to strengthen the presence of some criteria of the MCA by reflecting their emphasis in the TOR. These criteria should include the following:

- Inhibiting and unaffected constituents: to improve the removal of unaffected constituents, such as antibiotics, hormones, pharmaceutical compounds, and metals.
- Environmental constraints: public health risks are associated with direct exposure to wastewater or through accidents. The enclosure of the wastewater treatment is an important measure in addition to limiting the accessibility to trained professionals.
- Energy requirements: solar, hybrid systems, resource recovery (e.g., methane recovery) could supplement the energy usage and reduce energy consumption and, therefore, should be included in the TOR.
- Personnel requirements: Skills, experience, language, and HSE (PPE) training will be provided to responsible operators.
- Reliability: Maintenance- Durability could be significantly enhanced by providing long-term service contracts beyond the warranty period. This responsibility could be taken by KISR or by the supplier.
- Land availability: Land has proven to be an essential element in selecting the wastewater treatment unit. Thus, the footprint of the wastewater treatment will be given attention in the TOR, and/or securing the land ahead of procuring the unit is an important task.

IV. CONCLUSIONS

This paper aimed to develop a multi-criterion analysis (MCA) and selection tool for the best available packaged wastewater treatment system. The conclusions generated are the following:

- The MCA is an important tool to select best wastewater treatment system.
- The long-term monitoring revealed that the process performance could be represented by a set of criteria and corresponding parameters.
- The refinement of the MCA based on the long-term monitoring of wastewater treatment unit has further enhanced the MCA practicality.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

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