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Life-cycle analysis of environmental loads from household septic systems in Japan focusing on effluent water discharge

Iori Mishima[a,b,*], Naoki Yoshikawa[c,d], Susumu Asakawa[e], Yuji Noguchi[e] and Koji Amano[f]

[a] Center for Environmental Science in Saitama, 914 Kamitanadare, Kazo 347-0115, Japan
[b] Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo Sakura, Saitama 338-8570, Japan
[c] School of Environmental Science, The University of Shiga Prefecture, 2500 Hassaka-cho, Hikone 522-8533, Japan
[d] Department of Civil and Environmental Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu 525-8577, Japan
[e] Saitama-ken Environmental Analysis and Research Association, 1450-11 Kamiko Omiya, Saitama 330-0855, Japan
[f] College of Gastronomy Management, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu 525-8577, Japan
*Corresponding author. E-mail: mishima.iori@pref.saitama.lg.jp

IM, 0000-0001-7081-5940

ABSTRACT

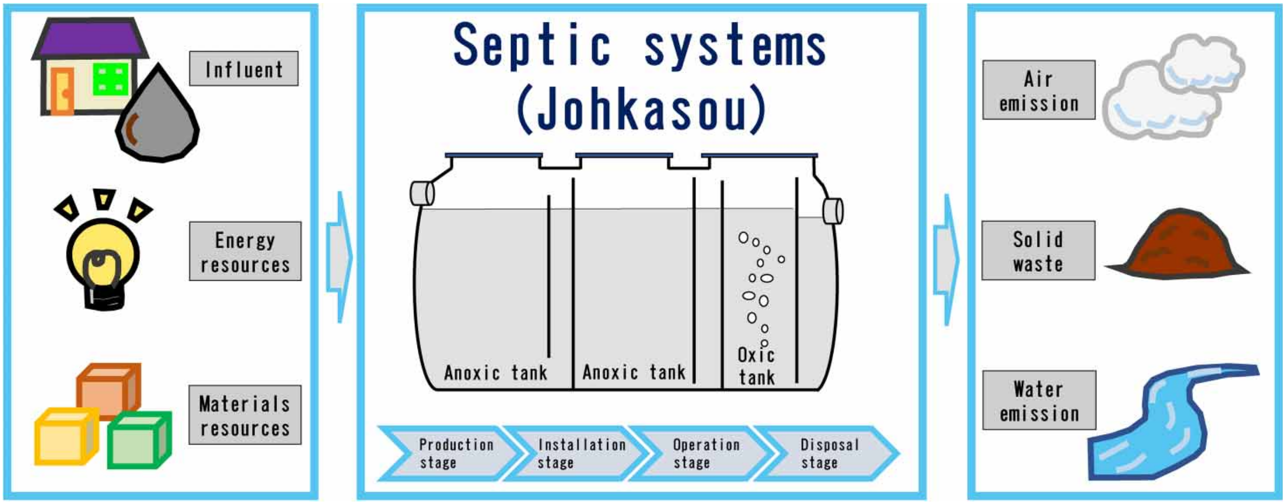
Various types of small-scale wastewater treatment systems are widely used in rural areas, and life-cycle assessment (LCA) should be performed to evaluate their environmental performance. In this study, septic systems were first classified into five categories based on their wastewater treatment performance. Effluent samples from actual systems were collected, and their water qualities were determined. A model to evaluate the environmental load from the septic systems using LCA methods was then established. The water-quality values obtained were input to the model, and the life-cycle environmental costs of the classified septic systems were calculated. The mean environmental load of the effluent during the operation stage was 37.6%, confirming that evaluation of an effluent discharge inventory using LCA, inspection, and water-quality monitoring to improve operations is critical for reducing the environmental load. The operation stage accounts for over 99% of the involved eutrophication, biological toxicity, and toxic chemicals, which are strongly related to the quality of the effluent. Evaluation of the effluent discharge inventory using LCA is of great significance, even for small-scale wastewater treatment systems. The set of procedures developed in this study can be used to calculate comprehensive environmental impacts at wastewater treatment plants.

Key words: effluent water quality, environmental cost, Johkasou, LCA, on-site wastewater treatment, tradeoffs

HIGHLIGHTS

- A model to evaluate the environmental load using LCA methods was established to discuss the importance of household septic systems.
- The water-quality values obtained from existing plants were input to the model, and the life-cycle environmental costs of the classified septic systems were calculated.
- Evaluation of the effluent discharge inventory was of great significance, even for small-scale wastewater treatment systems.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Life-cycle assessment (LCA) is extremely useful in the evaluation of modern water treatment-related infrastructure. Since the 1990s it has been used in several studies to evaluate the environmental impacts of urban wastewater treatment systems, particularly sewage treatment systems (Emmerson *et al.* 1995). These studies had different aims, scopes, and assumptions, and so the methods employed were also different. Wastewater treatment plants (WWTPs), for example, generally involve several processes, including infrastructure construction, wastewater treatment, sludge treatment, and sludge disposal. Most previous research on WWTPs evaluated only some of these processes. After reviewing 45 papers, Corominas *et al.* (2013) identified 22 studies in which the construction process was evaluated and 10 in which the sludge disposal process was excluded. Morera *et al.* (2017) developed a detailed inventory analysis of WWTP construction and investigated how the construction process contributes to the total environmental load in various impact categories. Comparison of the results obtained with those of seven previous studies showed that, according to most of these studies, the contribution of the construction process to climate change and freshwater eutrophication was 5–30 and <1–6%, respectively. Garfi *et al.* (2017) targeted relatively small-scale domestic wastewater treatment systems that served 1,500 person equivalents (PE), and assessed the environmental impact of three such systems: the conventional WWTPs (activated sludge systems), hybrid constructed wetlands, and high-rate algal pond systems. Of the four processes related to a conventional WWTP (i.e., construction, operation, sludge treatment and disposal, and emissions to air), the environmental impact of the operational process was most significant, being 85–97% of the total impact among all seven impact categories considered. These studies suggest that operation-related stages, including wastewater treatment, sludge treatment, and sludge disposal, are the main contributors to the environmental impact of conventional WWTPs (>90%). In addition to these studies, an increasing number of LCA studies are being conducted on large-scale WWTP systems and related processes (Hong *et al.* 2009; Lam *et al.* 2020; Zawartka *et al.* 2020; Liu *et al.* 2021).

Although LCA studies are not limited to wastewater treatment, they usually involve life-cycle impact assessment (LCIA) to compare the environmental loads of different impact categories. Recently developed LCIA methodologies, for example IMPACT World+ (Bulle *et al.* 2019), ReCiPe (Huijbregts *et al.* 2017), and LIME 2 (Itsubo *et al.* 2012), are damage-oriented approaches, wherein the damage at an endpoint (the areas of protection) is calculated. Multiple LCIA methodologies, including predecessors of these methodologies, have been applied to LCA case studies of wastewater treatment (Corominas *et al.* 2013; Sabeen *et al.* 2018; Gallego-Schmid & Tarpani 2019).

As expected, some existing studies in which the impact assessment step was taken into consideration illustrate that effluent quality is a key factor in the LCA of the environmental impact of wastewater treatment systems. Larsen *et al.* (2010) compared the environmental impacts of several wastewater treatment options, including conventional WWTPs, for multiple impact categories using the EDIP97 method (Wenzel *et al.* 1997). The wastewater treatment and sludge digestion process of the conventional WWTP was evaluated, and the decrease in the environmental impact due to nutrient removal was found to be approximately 18-fold that of similar processes without nutrient removal. Limphitakphong *et al.* (2016) evaluated the life-cycle environmental impact of WWTPs in Thailand in three impact categories: climate change, eutrophication, and acidification. The environmental impact that was normalized using LIME (Itsubo *et al.* 2004) showed that eutrophication accounted for over 90% of the total environmental impact. Therefore, it is important to assess effluent water quality thoroughly when comparing treatment options for wastewater with different effluent qualities.

Wastewater treatment in Japan includes sewerage systems in highly populated areas. However, in rural areas, septic systems (known as Johkasou in Japan) including Tandoku-shori septic systems and night-soil storage systems are used. Tandoku-shori septic systems and night-soil storage systems can only treat or store human waste from toilets; hence, they cannot treat gray water from sources such as kitchens, laundering, or baths. The use of night-soil storage systems is very limited and, in 2001, the installation of new Tandoku-shori septic systems was forbidden to reduce the environmental impact of gray water on the water environment. Therefore, at present, the septic systems (Johkasou) which can treat all domestic wastewater are the main individual, decentralized, and on-site wastewater treatment system employed in rural areas. Ebie *et al.* (2014) conducted a greenhouse gas (GHG) emissions survey on septic systems and clarified their emissions. Fujimura *et al.* (2017) studied septic systems and reported their biochemical oxygen demand (BOD) and nitrogen treatment performance, and the relationship between the recycle ratio and nitrogen treatment of the system. The technical aspects of the septic systems have been widely examined; however, there are few studies on the use of LCA to investigate their environmental impact. Thus far, LCA studies on large-scale wastewater treatment systems in Japan have focused primarily on assessing the total cost or GHG emissions of actual large-scale sewage treatment plants.

With respect to two impact categories, the integrated environmental loads of WWTPs were evaluated and compared using the LCIA method based on endpoint modeling ver. 2 (LIME2; Itsubo *et al.* 2012) and the ecotoxicity estimation model (Mishima *et al.* 2016). This approach was very useful in the evaluation of the integrated environmental load on climate change, eutrophication, and biodiversity. Wastewater treatment facilities consume large amounts of energy to improve pollution and discharge treated water. Because some pollutants remain in the treated water, it is necessary to evaluate the energy consumption and environmental load of the treated water comprehensively. Therefore, LCA can be used to evaluate the integrated environmental load, including effluent discharge to water environments, from septic systems to quantify the environmental performances of these systems. Today, several types of septic system such as the standard-structure type, BOD-removal type, nitrogen removal type, phosphorus removal type, and very compact type are operated to treat all domestic wastewater from individual houses.

When considering the aim of reducing environmental impact, it is desirable to select the type that improves water quality in areas where local water pollution is likely to be a problem. One that ensures a certain level of water quality and has less global environmental impact should be selected in areas where there is less demand for water-quality improvement. To promote this policy, economic measures such as a change in the subsidies for septic systems by local governments are possible. However, currently there is little quantitative information on the environmental impact that can be used as a basis for such measures. The objective of this study was to determine the integrated environmental performance from several types of septic systems, while quantitatively considering the specific features of each system using LCA.

2. MATERIALS AND METHODS

2.1. Classification of septic systems

The quality of wastewater from operational septic systems in Japan was investigated and LCA was performed on the water-quality data. For both procedures, septic systems were classified under five categories (Table 1). Septic systems consist of the sedimentation tank, anaerobic tank, aerobic tank, clarification tank, and disinfection tank. These systems can be classified into two types (K and C) based on their structure. The K-type, which is known as the standard-structure type, comprises systems designed and manufactured in compliance with the Structural Standards for Johkasou as prescribed by the Japanese government. C-type (C1–C4) septic systems, which are known as certified structure types, are freely designed and manufactured by septic system manufacturers and certified with the authorized effluent water quality based on the treatment performance test. These classifications and types are well known in the environmental administration and small-scale wastewater treatment industry in Japan. In general, the K-type septic systems are larger than the C-type systems. Most septic systems installed in the last decade have been the C-type. These are further divided into four subtypes (C1–C4) based on the type, authorized effluent water

Table 1 | Classification of septic systems into five categories

Classification	Targeted wastewater	Type	Authorized effluent water quality (mg/L)	Average volume of typical aeration tanks (m^3)	Average total volume of typical tanks (m^3)	Average total retention time (h)	Remarks
K	All domestic wastewater	Standard structure	BOD 20	1.03	2.95	57	
C1		Certified structure	BOD 20 (T-N 20)	0.45	2.10	40	
C2			BOD 10 T-N 20	0.62	2.74	53	
C3			BOD 10 T-N 10 T-P 1	0.73	2.89	55	Phosphorus removal type
C4			BOD 20 T-N 20	0.23	1.47	28	Very compact type

quality, and other functions (Table 1). The average volume of typical aeration tanks and average total volume of typical tanks, mainly based on data from the Johkasou System Association (2015), are also shown in Table 1. The quality of the effluent water from C1-type septic systems conforms to the BOD standards. C2 complies with a stricter standard than C1; in addition to the BOD standards, it complies with the standards for the removal of total nitrogen (T-N). C3 includes a phosphorus removal function with the electrocoagulation method using iron electrodes (Mishima *et al.* 2017, 2018) and complies with the strictest effluent standards, especially with respect to phosphorus concentration. Although the application of aluminum-containing pellets for phosphorus removal in septic systems has been explored (Fujimura *et al.* 2019), electrocoagulation using iron electrodes is the commonly adopted commercial technology. Therefore, among the C-type septic systems, the C2- and C3-types are larger and have long retention times for wastewater treatment. C4 is a compact septic system, and has a smaller tank than the conventional C-type septic systems. The average volume of typical aeration tanks, the average total volume of typical tanks and the average total retention time for five PE systems are also shown in Table 1.

2.2. Water-quality survey

The quality of the effluent treated using five categories of septic systems (Table 1) was investigated. The septic systems for five, seven, or 10 PE are planned and installed depending on the size of the house. Five and seven PE septic systems are commonly used; however, the actual size of households that use the septic systems varies. The actual/planned population ratio was estimated from the ratio of the actual number of occupants to the planned number of occupants to evaluate the influent load into each septic system (Ebie *et al.* 2014). The average of the actual/planned population ratio for approximately 12,000 existing septic systems in Saitama Prefecture was 0.56 ± 0.27. Therefore, to obtain effluent samples from septic systems with a standard load of wastewater, five PE systems that were actually used by two to four people and seven PE systems that were actually used by three to five people were selected. The sampling of the effluent from the selected septic systems was accompanied by annual legal inspection of the septic systems by a designated inspection organization in Saitama Prefecture, located around the center of Japan. The data from noncompliant septic systems were excluded from this investigation. Since these are individual septic systems, strictly speaking, the influent water quality and loadings are different. Therefore, we designed the study to investigate a large number of septic systems and to obtain an average value of effluent water quality. Because the number of C3 septic systems is limited, two to five PE C3 septic systems were selected and investigated once a month for approximately one year. The water quality of the sampled effluent was measured according to JIS K 0102 which is a Japanese industrial standard and used for water quality measurement. Chemical oxygen demand (COD) was not measured in the C3 survey. Therefore, COD was estimated by performing multiple regression analysis based on the data of BOD, NO_2-N and T-P obtained from other water-quality surveys (adjusted $R = 0.854$, $p < 0.001$). It had been verified that this COD estimation had no impact on the subsequent analysis of environmental impact assessment.

2.3. Life-cycle analysis

2.3.1. Scope definition and assumption

The LCA system boundary and analysis of the septic systems were set as shown in Figure 1. The septic system components are manufactured in factories and then transported to the installation sites. These systems have four life-cycle stages: production,

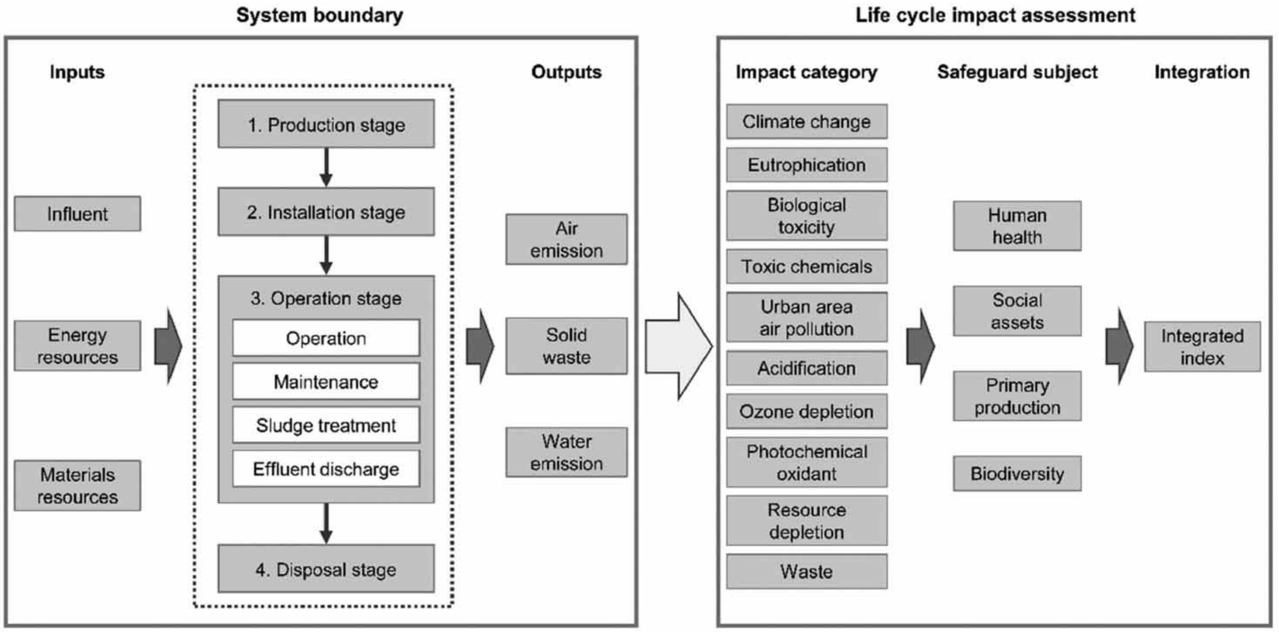


Figure 1 | Life-cycle assessment system boundary and analysis for septic systems.

installation, operation, and disposal. The production stage includes the fabrication of components, and the installation stage involves transportation from the factory to the installation site; both these stages require energy. Additionally, the systems are usually installed underground; therefore, energy is expended for the excavation and groundwork for installation. Operation, maintenance, sludge treatment, and effluent discharge are taken into account at the operation stage. Items such as material consumption, electricity consumption, direct GHG emissions, and indirect GHG emissions were considered in the operational process. The COD, T-N, total phosphorus (T-P), and ammonium nitrogen (NH_4–N) in the effluent were calculated for the effluent discharge. It was assumed that all septic system components to be disposed of at the end of the life cycle would be incinerated, and that the residues would be landfilled at the disposal stage.

For the operation stage, the average individual water usage in Japan was assumed to be 250, 50, and 200 L/p/d of all wastewater, black water, and gray water, respectively (Fujimura 2006). Additionally, the household size was assumed to be 3.03 people per household in 2015 (The Statistics Bureau of Japan 2017). This statistical value was obtained from a survey of the average household size of households with two or more people. The quality of the gray water influent was assumed to be: BOD, COD, T-N (100% as NH_4–N), and T-P of 145, 65, 10, and 1.5 mg/L, respectively (Fujimura 2006). The average amount of sludge generated was considered to be 1.2 L/p/d (Ministry of Health and Welfare 1988). The functional unit was considered to be 1-year use of a five PE septic system by one household, and the lifespan of a septic system was assumed to be 40 years. Throughout the life cycle of the septic system, 10 impact categories were considered: climate change, eutrophication, biological toxicity, toxic chemicals, urban area air pollution, acidification, ozone layer destruction, photochemical oxidant, resources depletion, and waste.

2.3.2. Inventory analysis

The technical parameters of the septic systems (i.e., rated electricity consumption and system components) were obtained from reports (Johkasou System Association 2015) and interviews with manufacturers. Information on 38 models, i.e., three, 18, 10, four, and three models from K, C1, C2, C3, and C4 categories, respectively, was collected. In addition to the principal model input data (Table 2), process data with parameters of the five categories with respect to manufacturing, transportation, and installation were mainly obtained from the Johkasou System Association (2015). These data were used to make estimates for systems with unreported process data. The disposed sludge is usually treated in excreta disposal treatment plants. Inventory data on the sludge disposal process were based on the existing reports (Matsui *et al.* 2002; Morikawa 2010; Ministry of Environment 2016; National Institute for Environmental Studies 2021). Table 3 presents detailed data

Table 2 | Principal model input data for the life-cycle assessment of septic systems

		K	**C1**	**C2**	**C3**	**C4**
	n	**3**	**18**	**10**	**4**	**3**
Production	FRP (kg)	166.7	96.0	145.7	125.1	67.0
	PVC (kg)	91	101.3	118.8	137.2	58.1
	Plastic (excl. FRP, PVC) (kg)	18.3	9	11.2	11.6	7.1
	Metals (kg)	8.0	7.5	11.0	19.4	0.6
Installation	10-ton track (t•km)	250				
	4-ton track (t•km)	110				
	Soil excavated (m^3)	5.7	5.2	5.7	6.1	5.6
	Rebar used (kg)	47.5	38.9	45.2	43.8	29.4
	Concrete used (m^3)	1.03	0.86	0.99	0.97	0.76
Operation	Electricity consumption of blower (W)	59.3	53.1	70.1	73.0	45.3
	Electricity consumption of phosphorus removal device (W)	0	0	0	6.7	0
	Electric pole (kg/year)	0	0	0	19.2	0
	Disinfectant (kg/year)	1.5				
	Travel distance of car for inspection (km/unit/year)	35.6				
	Travel distance of vacuum truck for sludge transportation (km/unit/year)	16.1				
	Amount of sludge (L/person/year)	438	438	438	438	438
Disposal	Disposal (kg)	284.0	213.8	286.7	1,061.3	132.8

FRP, fiber-reinforced plastics; PVC, poly vinyl chloride.

Table 3 | Process data of night-soil treatment

Utilities	Electricity	55.7	kWh/m^3	Morikawa (2010)
	Heavy oil	15.4	L/m^3	
	City gas	0.18	m^3/m^3	
	Sodium hydrate	1.30	kg/m^3	
	High-polymer coagulant	0.24	kg/m^3	
	Poly ferric sulfate	18.5	kg/m^3	
	Methanol	1.95	kg/m^3	
	Sodium hypochlorite	1.37	kg/m^3	
	Sulfuric acid	0.03	kg/m^3	
	Activated carbon (water treatment)	0.49	kg/m^3	
	Activated carbon (deodorization)	0.23	kg/m^3	
	Calcium hydrate	0.74	kg/m^3	
Greenhouse gas emissions	CH_4	0.005	$kgCH_4/m^3$	National Institute for Environmental Studies (2021)
	N_2O	0.0029	$kgN_2O/kg\text{-}N$	
Water quality of treated water	COD	9.5	mg/L	Ministry of Environment (2016)
	T-N	11	mg/L	
	T-P	1.9	mg/L	

of the sludge treatment process. Unit GHG emissions data from the septic systems were obtained from Yamazaki *et al.* (2014), which reported by septic system type: 2,477 (for K), 1,984 (for C1 and C4), 1,044 (for C2 and C3) g-CH_4/person/year and 71.7 (for K), 54.5 (for C1 and C4), 123.2 (for C2 and C3) g-N_2O/person/year in each septic system, respectively. GHG emission factors from discharged water and disposed sludge were referenced from National Institute for Environmental Studies (2021). The emission factors of natural decomposition of domestic wastewater were 0.06 kg-CH_4/kg-BOD and 0.0079 kg-N_2O/kg-N. The emission factors of septic system sludge treatment in a human waste treatment plant were 0.005 kg-CH_4/m^3 and 0.0029 kg-N_2O-N/kg-N. The Inventory Database for Environmental Analysis (IDEA) ver. 2 was used as a background data source.

2.3.3. Impact assessment

Finally, in accordance with the Japanese impact assessment model LIME2 (Itsubo *et al.* 2012) and the ecotoxicity estimation model (Mishima *et al.* 2016), each environmental load was converted into a monetary value (JPY) by multiplying it with the conversion factor. Although the LIME2 model considers 15 impact categories and many pollutant characterization factors reflecting Japanese conditions, it excludes some pollutants associated with the discharge of treated water. The ecotoxicity estimation model was used to evaluate the ecotoxicity effect of NH_4–N emissions into environmental water, a factor that can significantly affect aquatic life, including fish and crustaceans. This model was designed to be consistent with the LIME2 framework; therefore, both models were used to estimate the environmental impact in monetary terms. In addition, the ozone depletion potential of N_2O (Lane & Lant 2012) was considered.

3. RESULTS AND DISCUSSION

3.1. Water quality in treated water

The effluent water quality of 229 septic systems was measured (Figure 2). The maximum BOD sometimes exceeded 20 mg/L; however, it was generally maintained below the standard value (20 mg/L) for each type. Concentrations of BOD, T-N, and NH_4–N for C2- and C3-type septic systems were lower than those for other types because wastewater treatment was effectively performed with a long retention time in these types of systems. NH_4–N was much lower than T-N for the C2- and C3-types because of further nitrification; i.e., the oxidation of NH_4–N to NO_3–N under aerobic conditions was promoted owing to the longer retention time. T-P for the C3-type was significantly lower than that for the other types of system because

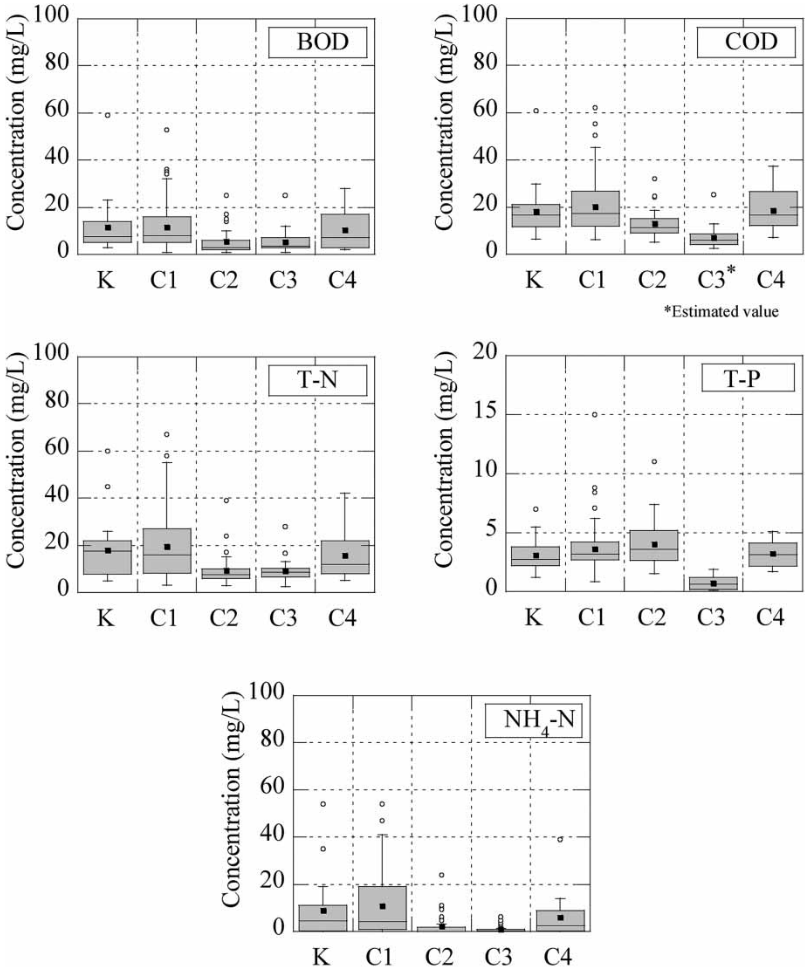


Figure 2 | Effluent water quality for all system types.

only C3 had a phosphorus removal function. Mishima *et al.* (2017) and Elazzouzi *et al.* (2018) reported that the electrocoagulation method for phosphorus removal can also remove dissolved organic carbon (DOC) simultaneously during the coagulation process. DOC was measured as a part of COD. Thus, it is regarded that the C3-type efficiently removed COD by the electrocoagulation method that was introduced as a phosphorus-removing function.

The T-N and T-P levels after treatment were found to be lower than their standard values in classifications targeting their removal for C1–C4. Based on these observations, the studied septic systems mostly operated properly, and a representative water quality for each type of system was obtained from this survey. The squares in Figure 2 indicate the average values that were used for the calculation of the environmental impact in effluent discharge.

3.2. Environmental impact in the operation stage

Determination of the environmental load of the effluent discharged during the operation stage and that of the influent was based on the mean values of effluent water-quality parameters (Figure 3). Organic nitrogen was included in the NH_4–N and used for calculation because it was regarded as having been converted to NH_4–N in the water environment. The load of NH_4–N was dominant in the influent, and most was removed in the effluent. The C1- and C3-types of septic systems had the highest and lowest overall environmental loads, respectively. Although there were differences among the categories, the environmental load in the effluent decreased in the order of T-P > NH_4–N > T-N, and the impact of COD was extremely low. Given that the C3 systems have the advantage of NH_4–N and T-P removal, their environmental load was the minimum. Generally, over 99% of eutrophication impact is caused by effluent discharge in all types of systems. The mean environmental load of the effluent obtained after the operation stage was 37.6%, and this evaluation of effluent discharge inventory using LCA was considered to be of great significance. The coefficients of variation for this environmental load from all water-quality survey data were 77, 65, 43, 57, and 53% for K, C1, C2, C3, and C4, respectively. These results imply that proper operation of the septic systems, inspections, and water-quality monitoring to confirm the effectiveness of the operation is critical for reducing the environmental load.

The environmental impact of GHG emissions in the operation stage by process is shown in Figure 4. The contribution of electricity consumption was the highest among all types of systems, followed by the direct emissions of the systems (CH_4 and N_2O) and the sludge treatment process. CO_2, CH_4, and N_2O emissions in the total GHG emissions of the operation stage were 64% (K) to 72% (C3); 11% (C3) to 25% (K); and 11% (C1) to 18% (C2), respectively. Approximately one-third of the global warming potential (GWP) was derived from non-CO_2 GHG. Generally, tradeoffs exist between greenhouse gases: septic systems with better effluent quality have lower CH_4 emissions and higher CO_2 and N_2O emissions. The main source of CO_2 emissions was electricity consumption of the septic system, and for the sludge treatment process, which accounted for 96 and 97% of GHG emission, respectively. CH_4 emissions were mainly related to the direct emission and sludge treatment process, and N_2O emission was mainly related to direct emission, indirect emission (from the effluent), and electricity consumption. This suggests that optimal control of the systems is important to reduce GHG emissions during operation. For C2 and C3 systems, with higher power consumption and large blowers, the values were slightly higher than those of the other systems. Direct GHG emissions and electricity consumption accounted for a significant

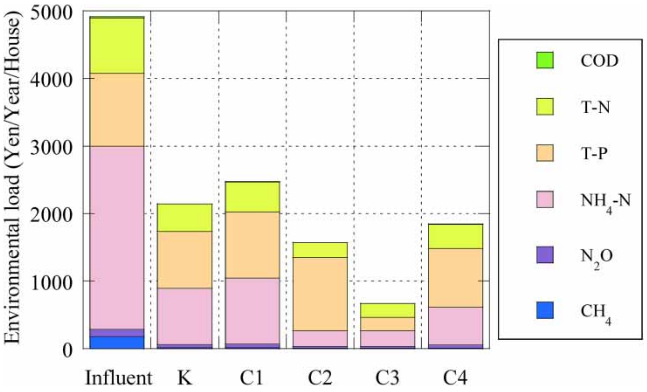


Figure 3 | Environmental loads of the effluent discharge compared with those of the untreated influent.

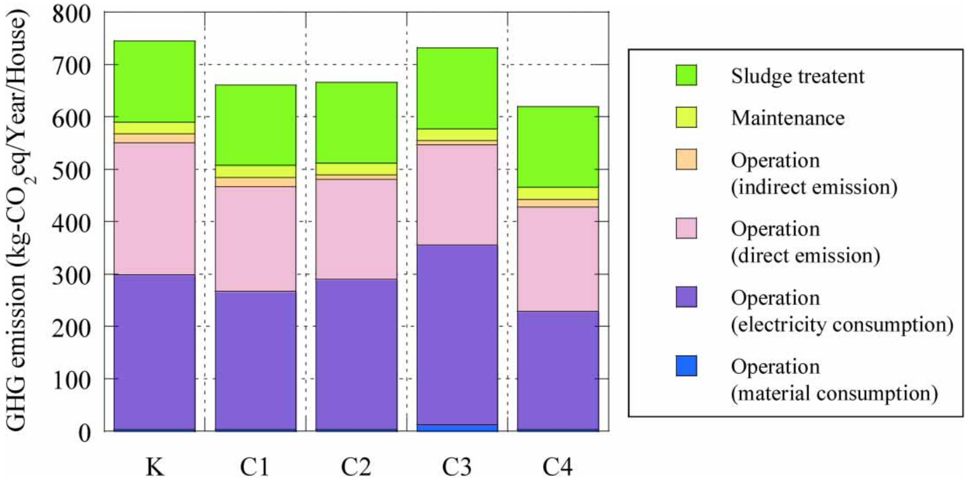


Figure 4 | Environmental impact of greenhouse gas emissions in the operation stage.

proportion of the overall global warming effect. Therefore, in the future, the development of energy-saving blowers or septic systems with low GHG (e.g., CH_4 and N_2O) emissions is desired.

Direct emissions were the CH_4 and N_2O emitted directly from septic systems. CH_4 emissions ranged from 3.16 (C2 and C3) to 7.51 kg-CH_4/year/house, which accounted for 41–74% of the total GWP of this process. Direct GHG emissions were lower in the systems with higher-quality effluent (C2 and C3) than in the others (K, C1, and C4). Indirect emission refers to CH_4 and N_2O emitted from the natural decomposition of effluent in a water environment. This emission depends on effluent quality: 0.5% of nitrogen is converted to N_2O, while the CH_4 emission factor is 0.06 kg-CH_4/kg-BOD (National Institute for Environmental Studies 2021). Furthermore, 71% (K, C1, C4) to 73% (C3) of indirect GHG emissions were derived from N_2O emissions. As with direct emission, higher-quality effluent, especially with lower nitrogen concentration, reduced the GHG emissions from the effluent. The direct emissions of C2- and C3-types of septic systems were both 190 kg-CO_2eq/year/house, whereas the highest was 252 kg-CO_2eq/year/house for the standard-structure type (K). Direct GHG emissions as CO_2 equivalent were 11.6 (C1) times to 23.4 (C3) times higher than that from the effluent. Hence, direct emissions were more critical than the effluent for reducing non-CO_2 GHG emissions related to the decomposition of water pollutants.

Tervahauta *et al.* (2013) reported that the highest primary energy consumption of 914 MJ/cap/year was attained within the centralized sanitation concept in an on-site wastewater treatment process that employed similar treatment methods to the septic systems in Japan. The primary energy consumption via electricity use by septic systems and sludge transportation systems, which corresponded to the system boundary of Tervahauta *et al.* (2013), was 1,173–1,763 MJ/cap/year. The difference between the two studies seems to be derived from scale, from a community-on-site (100–10,000 people) to a centralized system ($\geq$10,000 people), in contrast to an on-site (one household) system. Garfi *et al.* (2017) reported that the life-cycle GHG emissions of relatively small conventional WWTPs (1,500 PE, activated sludge system) were approximately 1.3 kg-CO_2eq/m^3. This was smaller than the results of this study, i.e., 2.3 (type C4) to 2.8 (type K) kg-CO_2eq/m^3, when the system boundary was modified to be consistent with the work of Garfi *et al.* (2017), excluding indirect emissions from the effluent and septic system disposal. The difference between these values was caused by multiple factors, mainly direct GHG emissions and electricity consumption. For example, in C4-type, the direct GHG emissions were 0.72 kg-CO_2eq/m^3, which is 22 times that reported by Garfi *et al.* (2017) (0.03 kg-CO_2eq/m^3). The electricity consumption of the C4-type system, including the sludge treatment process, was 1.72 kWh/m^3, whereas it was 1.26 kWh/m^3 in a conventional treatment plant. When comparing the two studies, note that the electricity consumption is higher at a smaller scale and that the septic system needs more aeration to circulate wastewater in the treatment tanks.

3.3. Total environmental impact of septic systems

The environmental loads for the total life cycle of the septic systems, including all the stages, are shown in Figure 5. A comparison of the stages demonstrates that the operation stage accounts for a significant proportion of the environmental load of the total life cycle of the systems: for example, it accounts for 96% of the load for C1 systems. Of the 10 impact categories, the

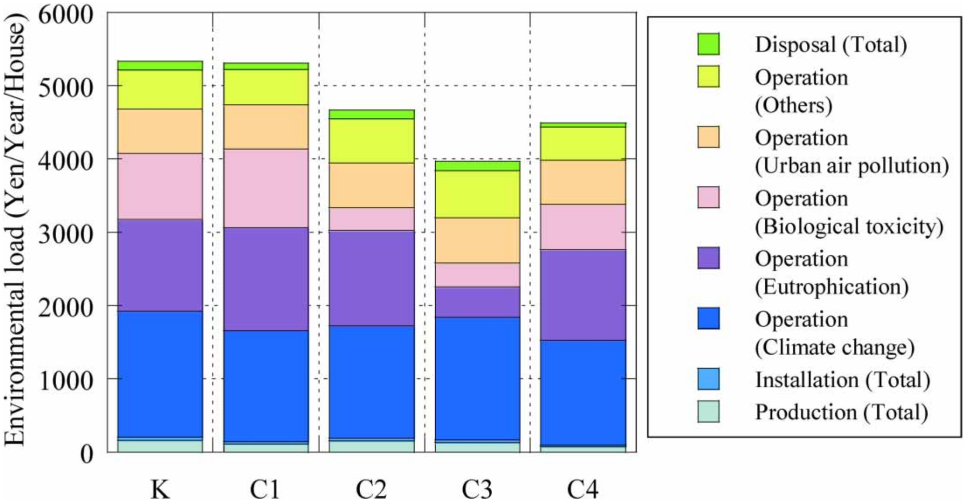


Figure 5 | Environmental loads of the total life cycle of septic systems, including all stages.

major contributors to environmental impact at this stage were climate change, eutrophication, and biological toxicity. Production and installation stages accounted for 2.2% (C4) to 4.3% (C3) of the total environmental impact, and both were significantly smaller than the impacts of the operation stage. This bias is the same as or stronger than that observed for large-scale WWTPs (Garfi *et al.* 2017; Morera *et al.* 2017) and other conventional aerated on-site (12–15 PE) wastewater treatment systems (Dixon *et al.* 2003; De Feo & Ferrara 2017).

Lehtoranta *et al.* (2014) compared the life-cycle GHG emissions and freshwater impact of seven options of on-site wastewater treatments for households in Finland. The life-cycle GHG emissions of the sequencing batch reactor and biofilter were approximately 500–600 kg-CO_2eq/year/household, which was slightly lower than the values reported in this study. The GHG emission hotspots were different from those in this study, i.e., sludge transportation as well as electricity and direct emissions. Moreover, the T-N load of the effluent in septic systems was lower (21 g/d). Similar to this study, the operation, including effluent and sludge treatment, accounted for much of the eutrophication potential in the study by Lehtoranta *et al.* (2014). Lam *et al.* (2015) evaluated conventional off-site and on-site wastewater treatment options with source-separated on-site treatment options in China. The conventional on-site treatment employed septic systems that corresponded to the C1-type system in this study. The life-cycle GHG emissions of the conventional option in China were approximately 180 kg-CO_2eq/person/year, which is slightly lower than that of the C1-type system in this study (231 kg-CO_2eq/person/year). The difference mainly arose from the inventory data of sludge treatment; the GHG emissions from other processes in the operation stage were similar in both studies. Regarding other impact categories that were common to the two studies (i.e., acidification and eutrophication), the impact in stages other than the operation stage was relatively low. The contribution of sludge disposal was higher in the report by Lam *et al.* (2015) in these two impact categories because of the assumptions of nutrient leaching and air emissions related to application to agricultural land. The impact on climate change accounted for 30.3% (C1) to 45.1% (C3) of the total environmental impact. Thus, any decision-making should be based on not only GHG emissions but also multiple environmental impacts, as shown in this study. The C3-type systems had the lowest environmental load owing to phosphorus reduction through iron electrolysis technology. Consequently, when the environmental loads of the nutrient removal and compact-type septic systems were calculated, the C3-type systems were found to have clearly performed better. A new C3-type system with fewer blowers and lower power consumption was developed recently. As this new type of system becomes mainstream, its advantages will become apparent.

The contribution of each stage for each impact category (Figure 6) shows that the operation stage makes the greatest contribution in all impact categories except waste. This stage accounted for over 99% of the eutrophication, biological toxicity, and toxic chemicals, which were strongly related to effluent quality. In contrast, the operation stage in urban area air pollution, which was related to industrial processes such as material manufacturing and transportation, had a relatively low contribution (82–90%). The amount of waste produced by the main unit contributed to the disposal stage, because the amount of landfill space occupied by the septic system itself was larger than that for the residue of incinerated sludge. The

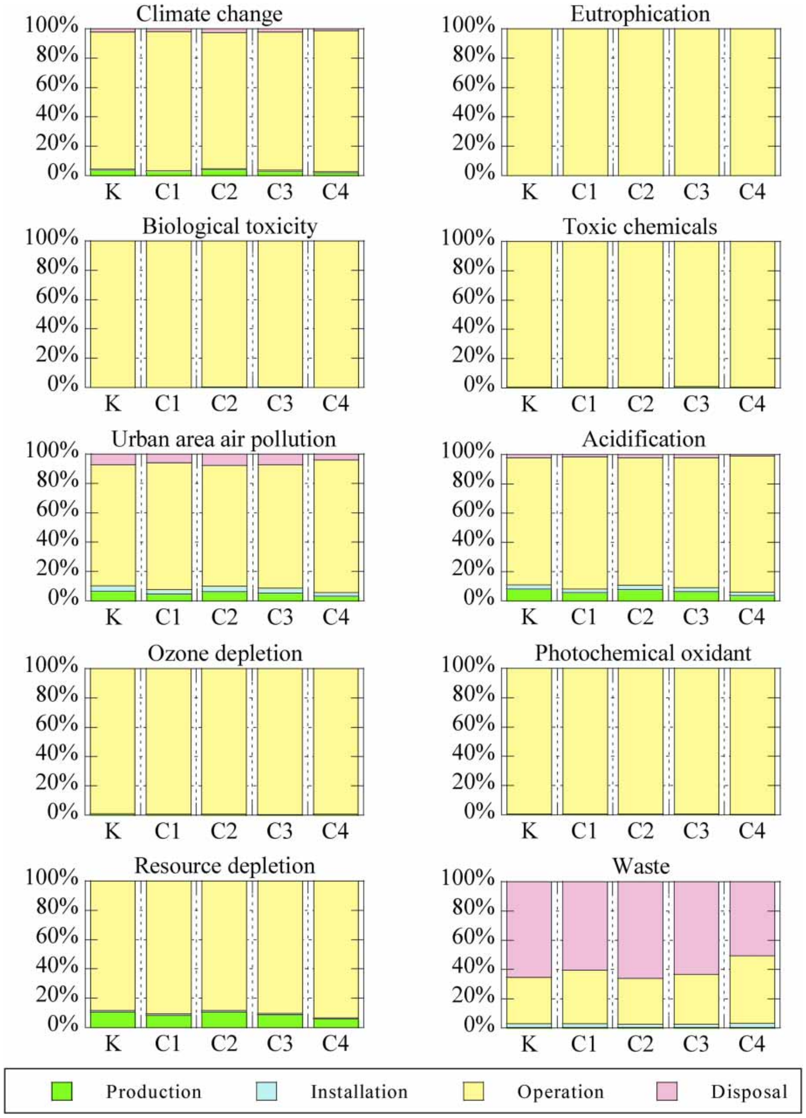


Figure 6 | Contribution of life-cycle stages to environmental impact categories.

percentage contribution of the disposal stage in the waste category was lower for C4-type systems because the main unit of C4 systems is smaller.

The relationship between the environmental load for climate change and eutrophication and biological toxicity taken together is shown in Figure 7. The lines with negative slopes indicate similar environmental impacts in terms of total GHG, eutrophication, and biological toxicity. This indicates that K- and C1-type systems had roughly the same impact for the three impact categories, which was higher than the impacts of the other septic systems. Between C3 and C4, the impact of effluent-related categories of the C3-type was the least for five categories, whereas the impact of climate change was the least for the C4-type. A tradeoff relationship between these parameters for these two systems was observed.

These results can be used as the basic information for the future management of the water environment by the local authorities or residents. For example, C3-type systems will be preferable for lakeside areas (Figure 7) because nutrient emission impacts on the water environment are more critical. In contrast, C4-type systems are preferable for areas where nutrient emission is not critical. Thus, the local government can recommend different types of septic system based on the tradeoffs of environmental impact and total cost of introduction. To the best of our knowledge, this is the first study to compare the multiple environmental impacts of septic systems based on on-site measurement of effluents. The results clearly show the

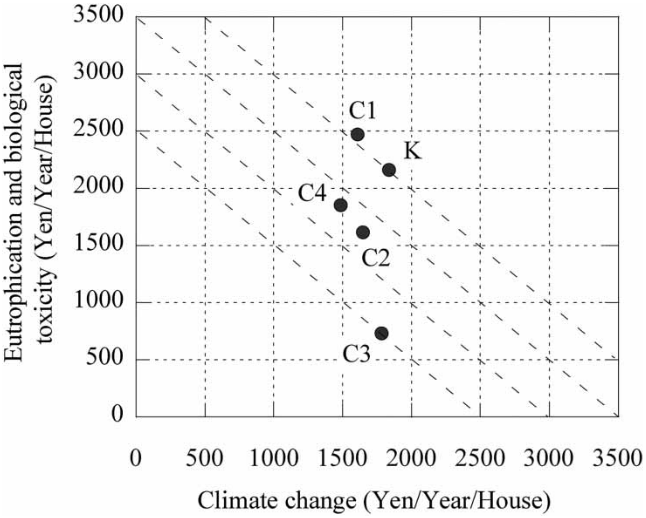


Figure 7 | Relationship between environmental load for climate change and eutrophication plus biological toxicity.

variations in the environmental profiles of different septic systems. The environmental load can be expressed as a monetary value using the model adopted in this study. Thus, it can be used to evaluate the government subsidy for introducing new technology for wastewater treatment. For instance, the benefits of the present septic systems, which can process all domestic wastewater, can be compared with those of the remaining Tandoku-shori septic systems, which can process wastewater from toilets only.

This method of study is innovative and challenging, and so the results obtained cannot currently be verified by comparison with other studies. The inventory data were not validated by comparison with other studies because no existing study provides comprehensive inventory data with detailed classification. Hence, more study results should be accumulated. LCA results are based on multiple assumptions. The values for various conditions such as household size, water consumption per capita, and background data on grid power are considered to be representative of the Japanese situation, but may differ from these values when evaluated in a specific region. The characterization factor for ammonia nitrogen biotoxicity is an estimate based on the conditions in Saitama Prefecture, and the factor may differ depending on the region. These points should be taken into account when applying the results of this study to other regions or when comparing them with other studies. Furthermore, the areal environmental impacts such as BOD, which causes poor oxygenation in the water environment and undesirable or discomforting odors, should be considered in future studies.

4. CONCLUSION

The water-quality data of effluents were collected, and LCA was performed, to enable a comprehensive and comparative evaluation of the environmental impact of septic systems. A model for evaluating the septic systems using LCA was developed, and the obtained water-quality data and system characteristics data were fed into the model. The results showed that the environmental load of the system with phosphorus removal was the minimum. The mean environmental load from the effluent in the operation stage was 37.6%. Therefore, evaluation of the effluent discharge inventory using LCA, inspections, and water-quality monitoring to demonstrate the proper operation of the septic systems is critical for reducing the environmental load. The operation stage accounts for more than 99% of eutrophication, biological toxicity, and toxic chemicals, which are strongly related to the quality of the effluent. The evaluation of an effluent discharge inventory using LCA is of great significance, even for small-scale wastewater treatment systems, in calculating the comprehensive environment impact.

This may be the first study to compare the multiple environmental impacts of septic systems based on on-site effluent measurement. The results clarify the differences in local and global environmental impacts for each type, and can be used to promote appropriate septic system installation in rural areas.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Bulle, C., Margni, M., Patouillard, L., Boulay, A. M., Bourgault, G., de Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R. K., Roy, P. O., Shaked, S., Fantke, P. & Jolliet, O. 2019 IMPACT world +: A globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment* **24**, 1653–1674. https://doi.org/10.1007/s11367-019-01583-0.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S. & Shaw, A. 2013 Life cycle assessment applied to wastewater treatment: State of the art. *Water Research* **47** (15), 5480–5492. https://doi.org/10.1016/j.watres.2013.06.049.

De Feo, G. & Ferrara, C. 2017 A procedure for evaluating the most environmentally sound alternative between two on-site small-scale wastewater treatment systems. *Journal of Cleaner Production* **164**, 124–136. https://doi.org/10.1016/j.jclepro.2017.06.205.

Dixon, A., Simon, M. & Burkitt, T. 2003 Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach. *Ecological Engineering* **20**, 297–308. https://doi.org/10.1016/S0925-8574(03)00007-7.

Ebie, Y., Yamazaki, H., Inamura, S., Jimbo, Y., Kobayashi, T. & Ueda, H. 2014 Development of emissions factor for the decentralized domestic wastewater treatment for the national greenhouse gas inventory. *Journal of Water and Environment Technology* **12** (1), 33–41.

Elazzouzi, M., Kasmi, A. E., Haboubi, K. & Elyoubi, M. S. 2018 A novel electrocoagulation process using insulated edges of Al electrodes for enhancement of urban wastewater treatment: Techno-economic study. *Process Safety and Environmental Protection* **116**, 506–515. https://doi.org/10.1016/j.psep.2018.03.006.

Emmerson, R. H. C., Morse, G. K., Lester, J. N. & Edge, D. R. 1995 The life-cycle analysis of small-scale sewage-treatment processes. *Water and Environment Journal* **9** (3), 317–325. https://doi.org/10.1111/j.1747-6593.1995.tb00945.x.

Fujimura, Y. 2006 Pollutant load factor of domestic wastewater and discharged loads from various on-site wastewater treatment facilities. *Journal of Water and Waste* **48** (5), 64–70. (in Japanese).

Fujimura, Y., Kiuchi, K., Amano, Y. & Machida, M. 2017 Performance evaluation of nitrogen removal type on-site treatment system for domestic wastewater. *Journal of Water Treatment Biology* **53** (4), 111–118. https://doi.org/10.2521/jswtb.53.111.

Fujimura, Y., Sugawara, M., Kondo, M., Inamori, Y., Inamori, R., Amano, Y. & Machida, M. 2019 Removal of phosphorus from domestic wastewater in actual on-site treatment systems using phosphorus removal pellets. *Japanese Journal of Water Treatment Biology* **55** (3), 67–77. https://doi.org/10.2521/jswtb.55.67.

Gallego-Schmid, A. & Tarpani, R. R. Z. 2019 Life cycle assessment of wastewater treatment in developing countries: A review. *Water Research* **153**, 63–79. https://doi.org/10.1016/j.watres.2019.01.010.

Garfi, M., Flores, L. & Ferrer, I. 2017 Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds. *Journal of Cleaner Production* **161**, 211–219. https://doi.org/10.1016/j.jclepro.2017.05.116.

Hong, J., Hong, J., Otaki, M. & Jolliet, O. 2009 Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. *Waste Management* **29**, 696–703. https://doi.org/10.1016/j.wasman.2008.03.026.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A. & van Zelm, R. 2017 Recipe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment* **22**, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Itsubo, N., Sakagami, M., Washida, T., Kokubu, K. & Inaba, A. 2004 Weighting across safeguard subjects for LCIA through the application of conjoint analysis. *The International Journal of Life Cycle Assessment* **9**, 196–205. https://doi.org/10.1007/BF02994194.

Itsubo, N., Sakagami, M., Kuriyama, K. & Inaba, A. 2012 Statistical analysis for the development of national average weighting factors – visualization of the variability between each individual's environmental thoughts. *The International Journal of Life Cycle Assessment* **17**, 488–498. https://doi.org/10.1007/s11367-012-0379-x.

Johkasou System Association 2015 *Report of Commissioned Study on low Carbonization and Overseas Expansion of Johkasou*. (in Japanese).

Lam, L., Kurisu, K. & Hanaki, K. 2015 Comparative environmental impacts of source-separation systems for domestic wastewater management in rural China. *Journal of Cleaner Production* **104**, 185–198. https://doi.org/10.1016/j.jclepro.2015.04.126.

Lam, K. L., Zlatanović, L. & van der Hoek, J. P. 2020 Life cycle assessment of nutrient recycling from wastewater: A critical review. *Water Research* **173**, 115519. https://doi.org/10.1016/j.watres.2020.115519.

Lane, J. & Lant, P. 2012 Including N_2O in ozone depletion models for LCA. *The International Journal of Life Cycle Assessment* **17**, 252–257. https://doi.org/10.1007/s11367-011-0362-y.

Larsen, H. F., Hansen, P. A. & Boyer-Souchet, F. 2010 *Decision Support Guideline Based on LCA and Cost/Efficiency Assessment (036845) EU FP6 Project*. No. 4.3, pp. 1–162. https://backend.orbit.dtu.dk/ws/portalfiles/portal/4674255/D4.3.pdf (accessed 7 November 2022)

Lehtoranta, S., Vilpas, R. & Mattila, T. J. 2014 Comparison of carbon footprints and eutrophication impacts of rural on-site wastewater treatment plants in Finland. *Journal of Cleaner Production* **65**, 439–446. https://doi.org/10.1016/j.jclepro.2013.08.024.

Limphitakphong, N., Pharino, C. & Kanchanapiya, P. 2016 Environmental impact assessment of centralized municipal wastewater management in Thailand. *The International Journal of Life Cycle Assessment* **21**, 1789–1798. https://doi.org/10.1007/s11367-016-1130-9.

Liu, W., Iordan, C. M., Cherubini, F., Hu, X. & Fu, D. 2021 Environmental impacts assessment of wastewater treatment and sludge disposal systems under two sewage discharge standards: A case study in Kunshan, China. *Journal of Cleaner Production* **287**, 125046. https://doi.org/10.1016/j.jclepro.2020.125046.

Matsui, Y., Yamada, M., Inoue, Y., Kawamura, K. & Tanaka, M. 2002 Life cycle inventory analysis of treatment facilities for liquid waste. *Journal of JSCE* **706** (VII-23), 19–29. https://doi.org/10.2208/jscej.2002.706_19 (in Japanese).

Ministry of Environment 2016 *FY 2015 Comprehensive Survey on Water Pollutant Discharge*. https://www.env.go.jp/water/report/h28-02/index.html (in Japanese) (accessed 7 November 2022).

Ministry of Health and Welfare 1988 *The Structural Guidelines for Night-Soil Treatment Plants*. Japan Waste Management Association, Tokyo (in Japanese).

Mishima, I., Yoshikawa, N., Yoshida, Y. & Amano, K. 2016 Development of an integrated environmental impact assessment model for assessing nitrogen emissions from wastewater treatment plants. *Journal of Water and Environment Technology* **14** (1), 6–14.

Mishima, I., Hama, M., Tabata, Y. & Nakajima, J. 2017 Improvement of phosphorus removal by calcium addition in the iron electrocoagulation process. *Water Science & Technology* **76** (4), 920–927. https://doi.org/10.2166/wst.2017.256.

Mishima, I., Hama, M., Tabata, Y. & Nakajima, J. 2018 Long-term investigation of phosphorus removal by iron electrocoagulation in small-scale wastewater treatment plants. *Water Science & Technology* **78** (6), 1304–1311. https://doi.org/10.2166/wst.2018.402.

Morera, S., Corominas, L., Rigola, M., Poch, M. & Comas, J. 2017 Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. *Water Research* **122**, 614–623. https://doi.org/10.1016/j.watres.2017.05.069.

Morikawa, N. 2010 On improvement of night-soil treatment facilities: Focusing on CO_2 emission reduction. *JEFMA* **58**, 27–30. (in Japanese).

National Institute for Environmental Studies 2021 *National Greenhouse Gas Inventory Report of JAPAN 2021*. https://www.nies.go.jp/gio/archive/nir/jqjm1000000×4g42-att/NIR-JPN-2021-v3.0_GIOweb.pdf (accessed 7 November 2022).

Sabeen, A. H., Noor, Z. Z., Ngadi, N., Almuraisy, S. & Raheem, A. B. 2018 Quantification of environmental impacts of domestic wastewater treatment using life cycle assessment: A review. *Journal of Cleaner Production* **190**, 221–233. https://doi.org/10.1016/j.jclepro.2018.04.053.

Tervahauta, T., Hoang, T., Hernández, L., Zeeman, G. & Buisman, C. 2013 Prospects of source-separation-based sanitation concepts: a model-based study. *Water* **5**, 1006–1035. https://doi.org/10.3390/w5031006.

The Statistics Bureau of Japan 2017 *Population Census*. https://www.stat.go.jp/english/data/kokusei/index.html (accessed 7 November 2022).

Wenzel, H., Hauschild, M. & Airing, L. 1997 Environmental assessment of products. In: *Vol. 1-Methodology, Tools and Case Studies in Product Development,* 1st edn (Wenzel, H., Hauschild, M. Z. & Airing, L., eds). Chapman & Hall, United Kingdom. Kluwer Academic Publishers, Hingham, MA, USA. ISBN 0-412-80800-5

Yamazaki, H., Ebie, Y. & Ueda, H. 2014 Methane and nitrous dioxide emissions from decentralized wastewater treatment facilities. *Journal of Water and Waste* **56** (10), 41–48. (in Japanese).

Zawartka, P., Burchart-Korol, D. & Blaut, A. 2020 Model of carbon footprint assessment for the life cycle of the system of wastewater collection, Transport and Treatment. *Scientific Reports* **10**, 5799. https://doi.org/10.1038/s41598-020-62798-y.

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