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SUSTAINABLE FOOD PRODUCTION AND CONSUMPTION

Life cycle environmental and economic impact of a food waste recycling-farming system: a case study of organic vegetable farming in Japan

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Abstract

Purpose Bio-based recycling systems and agricultural production using recycled materials are often evaluated separately. This study performs an environmental and socio-economic life cycle assessment (LCA) of a food waste treatment and spinach farming system in Japan. The environmental and economic tradeoffs of introducing a recycling system and the net environmental benefit of the substitution of market fertilizer considering operation changes are also examined.

Methods Three scenarios were developed and compared. In the conventional (CV) scenario, food waste is collected, incinerated, and disposed of in landfill, and the farmer uses market organic fertilizer. The on-site composting (OC) scenario processes food waste using an on-site garbage disposer and transports compost to a nearby spinach farmer. Food waste in the centralized composting (CC) scenario is transported to a centralized composting facility and resultant compost is sent to the farm. Primary data were obtained from field experiments and interviews. Non-greenhouse gas (GHG) emissions from the field and nitrogen leaching to water systems were simulated using the denitrification–decomposition (DNDC) model. The environmental LCA targeted climate change, eutrophication, and waste landfill. An input–output analysis estimated socio-economic indicators, namely gross added value and employment inducement effect.

Results and discussion The scenario with the lowest impact is the CC scenario. Climate change and eutrophication impacts are highest in the OC scenario and waste landfill impacts are most significant in the CV scenario. The weighted impact by LIME2 can be reduced by 47% in the CC scenario and 17% in the OC scenario due to the recycling of food waste instead of dumping in the landfill. The difference in socio-economic indicators between the scenarios was relatively small, although the CV scenario encouraged more employment. The substitution effect of composting, as well as the environmental impact reduction of replacing market organic fertilizer with compost, will result in 28.7% of the avoided impacts in GHG emissions.

Conclusions Both composting scenarios are feasible from an environmental and socio-economic perspective when compared with conventional organic production, although there is a tradeoff between waste landfill and GHG emissions for the on-site composting system. However, the OC scenario needs to save electricity to improve its environmental competitiveness with the CV scenario. When considering the substitution effect of composting, it is recommended to take into account that agricultural operation also changes.

Keywords Food waste composting · On-site composting · Spinach farming · LCA · Gross value added · Induced employment · Substitution effect

1 Introduction

Reducing and recycling food waste recently became an urgent issue for sustainable food systems. Recycling food waste creates new resources and can improve the environmental and economic impacts of the food system. A closed food loop by recycling nutrients in food waste is among the most important ways to improve mineral nutrient efficiency, as well as national and global food security

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(McConville et al. 2015). A life cycle approach assists with decision-making on how to close food loops under the varying conditions of local areas, by considering the entire food system, which consists of consumers, the agri-food sector, and the waste management sector.

Focusing on the current situation of waste generation, the occurrence of patterns of food loss and food waste in the food supply chain is globally diverse (Meybeck et al. 2011). In Japan, food waste generation (including non-edible parts) in 2016 was estimated to be 27.6 million tons, and 71% of this waste was derived from business activities (MoE 2019). The recycling ratio of food per business sector differs vastly, with 95% recycled in the food manufacturing industry, 67% in the wholesale industry, 51% in the retailing industry, and 32% in the food service industry (MAFF 2019). Therefore, improving the "3Rs" (reduce, reuse, and recycle) in the foodservice and retailing industries, and of consumers, is a primary challenge. The Japanese Government is currently supporting recycling companies, agricultural producers, retailers, and food service companies, thereby promoting the "food-recycling loop."

Until now, most studies have focused on the comparative life cycle assessment (LCA) of food waste recycling options from food processing (Laso et al. 2016; Ogino et al. 2007), retailers (Brancoli et al. 2017; Eriksson and Spångberg 2017; Mondello et al. 2017), food service sector (Hodge et al, 2016; Franchetti 2013), and municipal food waste, including household kitchen garbage (Edwards et al. 2018; Salemdeeb et al. 2017; Sonesson et al. 2000; Tonini et al. 2020). The majority of these assume centralized waste treatment, and fewer studies assess on-site recycling of the commercial sector. For example, Mu et al. (2017) performed an LCA of the environmental impact and economic cost/benefit of composting food waste from a university campus in the USA. Their study focused on an in-vessel composting system, which includes waste collection, composting, growing vegetables from this compost, and providing these vegetables for consumption in the student cafeteria. The study revealed that such a system can reduce greenhouse gases (GHGs) and diminish the impact of eutrophication compared with landfilling. The benefits of this particular system exceeded its costs when the selling of vegetables was taken into consideration. Another study by Yeo et al. (2019) performed LCA of a novel on-site organic waste decomposing instrument by comparison with centralized treatment (landfilling and anaerobic digestion) in Hong Kong. While a pilot-scale study (20 kg/day) generates more life cycle GHG emissions than a conventional treatment system, a full-scale scenario (200 kg/day) is expected to reduce emission rates.

Nevertheless, on-site organic waste recycling systems have the potential to reduce environmental load from conventional waste treatment systems. However, additional research is needed to bridge the gaps in knowledge.

Existing studies are primarily focused on the recycling processes of the system; they do not consider how agricultural operations might change with the use of alternative fertilizers. Recycled material is not strictly an alternative to virgin materials. For example, compost and chemical fertilizer supply nutrients. However, their characteristics are different (e.g., concentration of nutrients, form of nitrogen and phosphorus, and content of organic matter). This will be a key consideration in the evaluation to determine whether this kind of system could become sustainable as it is related to the merit of agricultural producers. Furthermore, the majority of LCA research employs an IPCC Tier I/II approach (Klein et al. 2006) to estimate GHG from agricultural activities, such as soil N_2O emissions (Goglio et al. 2014). However, this approach insufficiently considers variability in site-specific conditions, including crop management, climate, and soil (Goglio et al. 2018, Li et al. 2001). Alternative approaches (e.g., agroecosystem models) can be used to more closely estimate the observed emissions in site-specific conditions (Goglio et al. 2018).

Furthermore, the impacts on the regional economy are often considered when analyzing regional systems. Chen et al. (2019) evaluated the socio-economic impact of nutrient recycling within the rice production system, employing gross value added as an indicator. Finley et al. (2018) compared countywide statistics data in the USA and concluded that organic farming will present opportunities for job creation beyond those provided by conventional agriculture. However, to date, the economic and environmental impacts of food-recycling-farming systems have not been comprehensively analyzed.

Based on these research questions, this study aimed to determine the impacts of a food waste treatment and farming system on the environmental load and regional economy by conducting an LCA case study in Japan.

2 Materials and methods

2.1 Goal and scope definition

This study selected a greenhouse organic spinach farm in Japan to achieve the research aims. The farm investigated is located in the southern part of Shiga prefecture, which is in the vicinity of the large cities of Kyoto and Osaka, and approximately 2 km away from a university.

This particular farm was selected because it is near the university, where food waste is generated; thus, it could be expected that there would be more merit to composting owing to short transportation distance. The possibility of field testing is another reason why this farm was targeted. This farm conventionally uses market organic fertilizer made with domestic and imported organic ingredients; the use of agrochemicals is avoided. The farmer cultivates leafy vegetables four times per year, while greenhouses are used to prepare rice nurseries for several months.

The university campus has approximately 15,000 students and several cafeterias, cafes, and restaurants. Food waste from these food services was not recycled prior to this study, instead, they were sent to an incineration facility of the regional government.

The goal of our assessment was to compare the life cycle environmental load and regional socio-economic effect of composting food waste from the university campus and using this compost at the targeted organic farm. Three scenarios were developed to assume options considering the difference in agricultural practices and also composting technologies.

The system boundary included the collection, treatment, composting of food waste, transportation of compost, production of market organic fertilizer, and cultivation of spinach. Fig. 1 illustrates the system boundary and scenarios. The details of the scenarios are presented in Sect. 2.2. Climate change and eutrophication impacts were also evaluated.

Two types of functional units are defined in this study: 1 kg of spinach production and 1 ha of spinach cultivation, to examine the product-based and activity-based results. The system also contained the treatment of food waste. A total of 25 t/ha of food waste were used; therefore, a functional unit "1 ha" includes 1 ha of vegetable cultivation and the waste treatment of 25 t of food waste. A weight-based functional unit includes the waste treatment of 25 (t/ha) divided by the yield (kg/ha) in each scenario.

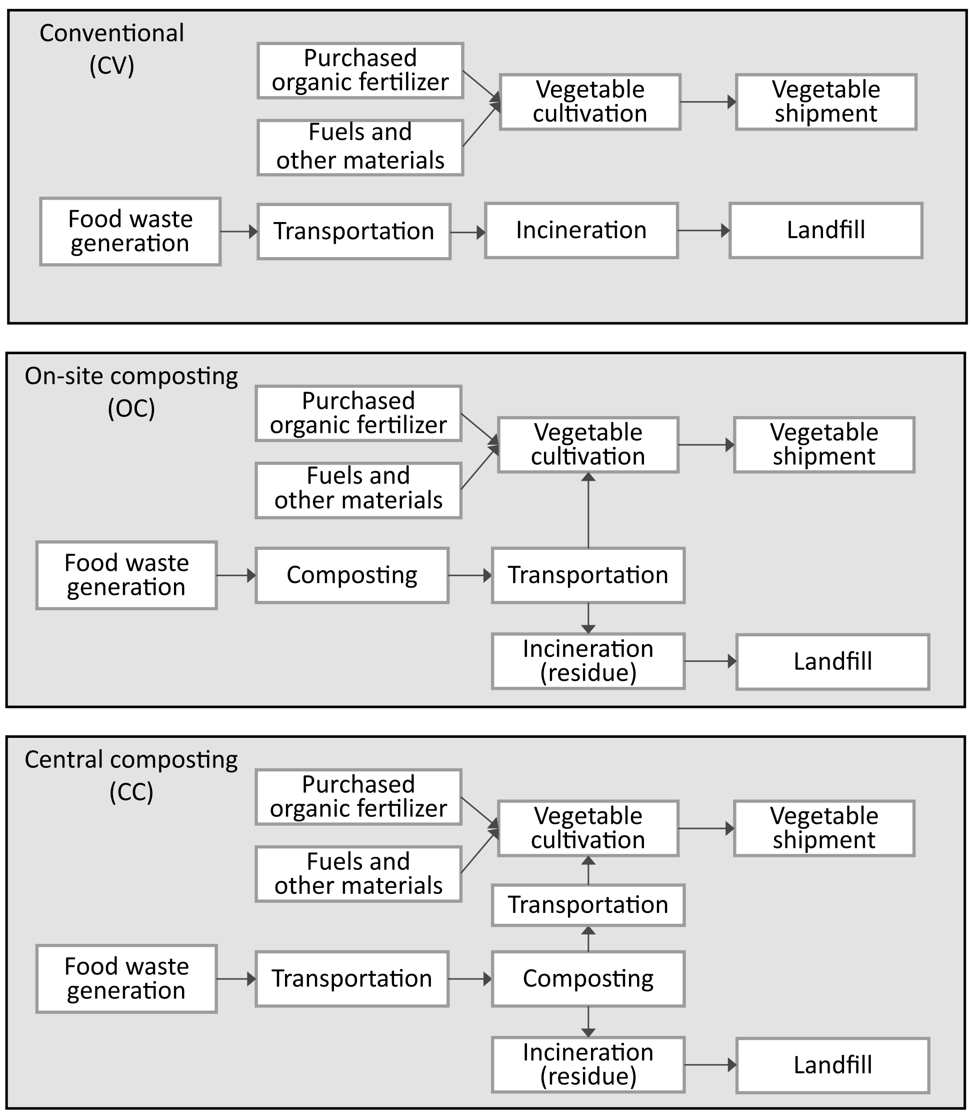

Fig. 1 System boundary of three scenarios

2.2 Scenarios and primary data collection

Three scenarios were developed in this study to consider the options of food waste composting. The first scenario is conventional (CV). This scenario assumes a real situation of a target university (Ritsumeikan University), while the other scenarios are prospective assessments based on pilot experiments. Food waste from the university campus is collected, incinerated, and transported to the landfill. Energy recovery during the incineration process was not considered.

The municipal waste incineration facility of the city in which the university is located had not introduced any energy recovery facility at the moment of field testing. This is not a rare case because 38% of the 1030 municipal waste incineration facilities in Japan had not introduced any energy recovery facility in 2016.

The target farm uses market organic fertilizer (made from animal and vegetable ingredients, expecting relatively quick mineralization) and produces organic spinach. The second scenario is an on-site composting (OC) scenario. In this scenario, food waste is processed by the composting machine (garbage disposer SANYO GNS-50, capacity: 50 kg per day) located at the university and represents primary fermentation. The processed compost is then collected by the farmer and used for organic spinach cultivation. The last scenario is a centralized composting (CC) scenario. Food waste in this scenario is transported to a centralized composting facility (capacity: 25 tons per day). The compost is then sent to the selected farm in the study area and used for organic spinach cultivation. The distance from the centralized composting facility to the farm and university is approximately 5 km. In all three scenarios, we assumed that the vegetables produced are sold to the local community.

Most of the primary data of the agricultural process were obtained from exploratory cultivation (around 400 m^2 scale) at the study site. An overview of the result of the test cultivation is shown in Table 1. There is some difference in the amount of nitrogen input to the field; however, it should decrease when considering the lower mineralization ratio of food compost (Takemoto 2006). The substitution of fertilizer was not controlled strictly, while considering soil carbon and nitrogen content of the both experimental plots, as well as compost availability for the field testing. Amount of available nitrogen applied was close, 10.0 kg N/10a (food compost) and 11.0 kg N/10a (conventional) when assuming the mineralization ratio of nitrogen as 60% for market organic fertilizer (Taki et al. 2008; Sato 2010) and 20% for food compost (Nakazawa and Sato 2004; Iwasa et al. 2010).

The usage data of seeds, fertilizers (food waste compost and market organic fertilizer), fuels, and labor input were collected by interviewing the farmer. The schedule of cultivation was also surveyed to simulate nitrous oxide (N_2O) and methane (CH_4) emissions (see Sect. 2.3). The input data of the waste incineration process, such as electricity, fuels, and chemicals, were obtained from Amano and Sowa (2007); they are inventory data derived from interviewing representatives of the regional governmental waste incineration facility (Stoker furnace, capacity: 150 t/day) near the farm. The life cycle process data of market organic fertilizer production were made based on information from the product manufacturer on the average content of fertilizer and energy consumption at the factory. The electricity consumption of the composting machine was also measured, and no consumptive materials were used for the on-site composting process. Primary data for the centralized composting process were derived from the model

Table 1 Overview of spinach cultivation

		Food compost	Organic (conventional)
Cultivation period	Seeding	Late October, 2016	Late October, 2016
	harvest	Late December, 2016	Mid-January, 2017
Area of greenhouse (m^2)		201	288
Yield (kg/10a)		896	778
Fertilizer	Type	Food compost (N 2.5%, P_2O_5 0.2%, K_2O 0.6%) Commercial organic fertilizer (N 8%, P_2O_5 4%, K_2O 4%)	Commercial organic fertilizer (N 8%, P_2O_5 4%, K_2O 4%)
	Amount (kgN/10a)	29.2	16.7
Operation	Tillage	Machine	Machine
	Fertilization	Manual	Manual
	Agrichemicals	No use	No use
Mean daily maximum temperature (°C)		13.0	12.4
Mean daily minimum temperature (°C)		5.5	5.0

facility data (Yuyama et al. 2006), indicating a capacity of 25 t/day.

2.3 Environmental LCA

Inventory analysis was performed using foreground data, as explained in Sect. 2.2, and background data, from the Japanese life cycle inventory database IDEA v2.3 with Microsoft Excel 2019. Inventory data included consumptive goods, while durable goods, such as machines and greenhouses, were excluded from the calculation.

In addition, non-GHG emissions from the field and NH_3 volatilization were simulated using the denitrification–decomposition (DNDC) model to reflect the differences between the practices. The DNDC model is a process-based model of carbon and nitrogen biogeochemistry used to model agricultural ecosystems (Li et al. 1994). This model requires input parameters related to climate, such as soil, vegetation, and human activity (e.g., tillage, fertilization, and residue management), to simulate GHG emission through two component sub-models (soil climate, crop growth, and decomposition sub-model and the nitrification, denitrification, and fermentation sub-model, see Fig. 2). Model simulation has been performed for the last 20 years to stabilize the model output (Fumoto et al. 2008), assuming the same crop rotation and using past weather measurement data from nearby meteorological offices. Information of practice from farmers and soil analyses are used for the simulation and interpretation of results. For fertilization, nitrogen and carbon content as well as timing of application were the input parameters. Temperature data in the cultivation period were measured directly in the field (Table 1). The average of the model output from the last 10 years was used for the LCA.

Phosphorus and nitrogen leaching from the agricultural field was estimated separately from the DNDC model. It was assumed that 0.1% of the phosphorous from the fertilizer leached into the environment (Hirata et al. 1986). For nitrogen leaching, the surplus nitrogen of the field, which is nitrogen input from fertilizer minus the output by crop harvesting, was calculated. Based on this, we determined that nitrogen leaching is responsible for 20% of the surplus nitrogen (Hokazono and Hayashi 2012). The dry matter based nitrogen and phosphorus content of spinach is 49.3 g N/kg and 5.4 g P/kg, respectively (Nakamura and Yuyama, 2005).

For the composting process, the emission factors of CH_4 and N_2O were derived from MoE and NIES (2019) and Hirai et al. (2001), respectively. These emission factors were assumed to be equal for the CC and OC scenarios. It is assumed that 48.6% of volatilized nitrogen in the composting process is in the form of NH_3, which is estimated from the middle case in Guardia et al. (2010), and 34.5% of nitrogen in food waste is volatilized (Yuyama et al. 2006).

Inventory data including the output of the DNDC model are shown in Table 2. The impact assessment model LIME2 (Itsubo and Inaba 2012) was used in the impact assessment for both characterization and weighting to reflect the environmental and social situation in Japan. This study considered climate change, acidification, ozone depletion, eutrophication, resource depletion, and waste landfill. The choice of impact categories was limited because it is expected that the three are to be critical on the food waste treatment and agricultural production system; furthermore, the impact categories are excluded if foreground data is not obtained (e.g., toxic chemicals are excluded because site-specific emission data from waste incineration is not obtained). The impact category of waste landfill was developed in LIME2 reflecting high concern as an environmental problem in Japan, while waste landfill is not commonly established in

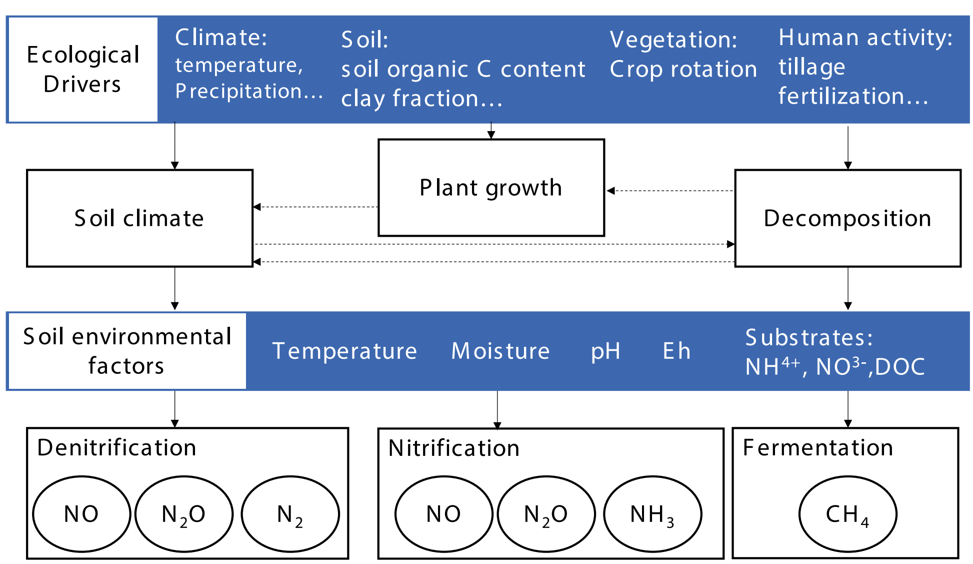

Fig. 2 Structure of DNDC model (modified from Li (2000))

Table 2 Inventory data by scenario per 10a

		Unit	Centralized composting (CC)	On-site composting (OC)	Conventional (CV)
Fertilizer and compost production					
	Electricity	kWh	192.2	1844.5	-
	Tap water	m^3	0.3	-	-
	Heavy oil	L	20.5	-	-
	Diesel	L	13.5	-	-
	Truck transportation	tkm	9.5	-	-
	Market organic fertilizer	kg	162.5	162.5	208.0
Direct emission from composting					
	N_2O	kg N_2O	0.169	0.169	-
	CH_4	kg CH_4	0.192	0.192	-
	NH_3 (air)	kg NH_3	2.09	2.09	-
Transportation of input materials					
	Gasoline	L	0.5	0.5	0.7
Fuel for cultivation					
	Diesel	L	10.1	10.1	7.2
Field emission					
	N_2O	kg N_2O	0.33	0.33	0.32
	T-N (leaching)	kg N	5.17	5.17	2.74
	T-P (leaching)	kg P	0.002	0.002	0.008
	NH_3 (air)	kg NH_3	0.013	0.013	0.010
Crop shipping					
	Diesel	L	8.1	8.1	7.0
	Polypropylene	kg	4.9	4.9	4.2
Agricultural labor					
	Crop cultivation	hour	29.3	29.3	26.9
	Crop shipping	hour	234.6	234.6	203.7
Treatment of food waste					
	Electricity	kWh	2.9	2.9	594.9
	Heavy oil	L	0.1	0.1	11.3
	Diesel	L	0.03	0.03	5.80
	Coagulation aid	kg	0.000	0.000	0.004
	sodium hydroxide	kg	0.00	0.00	0.27
	Ferric chloride	kg	0.01	0.01	2.60
	Chelate agent	kg	0.02	0.02	5.13
	Slaked lime	kg	0.18	0.18	36.88
	Final disposal	kg	2.3	2.3	483.3

other impact assessment methodologies (Itsubo and Inaba 2012). Using the LIME2 model, environmental impacts can be integrated and represented as economic values (Japanese Yen).

2.4 Socio-economic assessment

A socio-economic impact can be assessed using various quantitative and qualitative indicators. To assess quantitatively for each scenario, the induced gross value added and employment inducement effect were used. An input–output (IO) analysis using the Japanese IO table in 2011 (MIC 2016), consisting of approximately 400 industrial sectors, was used to quantify these indicators. The domestic and overseas effects were calculated separately to analyze how much the effect remains domestically.

Both indicators considered primary and secondary effects. Primary effects refer to the production change of industries through demand by waste management and the use of agricultural technologies for each scenario. Secondary effects are the production changes made by private (household) consumptive expenditure through wage increases by primary effect. Calculation of the induced gross value added is shown in Eqs. (1)–(5), based on Ito and Takano (2014). The first terms on the right side of Eqs. (1) and (2) indicate the primary effect, and the second terms describe the secondary effect.

$$E = g(I - A)^{-1}f + g(I - A)^{-1}Y \tag{1}$$

$$E_{\mathrm{d}} = g\left[I - \left(I - \widehat{M}\right)A\right]^{-1}f + g\left[I - \left(I - \widehat{M}\right)A\right]^{-1}Y_{\mathrm{d}} \tag{2}$$

$$Y = \bar{c}kw(I - A)^{-1}f \tag{3}$$

$$Y_{\mathrm{d}} = k\bar{c}w\left(I - \widehat{M}\right)\left[I - \left(I - \widehat{M}\right)A\right]^{-1}f \tag{4}$$

$$E_{\mathrm{o}} = E - E_{\mathrm{d}} \tag{5}$$

where E is the induced gross value added, E_{d} is the induced gross domestic value added, E_{o} is the induced gross overseas value added, A is the input coefficient matrix, g is the vector of gross value added factor, f is the demand vector by scenario (final demand of spinach and waste management), M is the diagonal matrix import coefficient, Y is the demand vector of private consumption (household), Y_{d} is the demand vector of private consumption (household) of domestic products and services, k is the average composition of consumption per sector, $\bar{c}$: is the marginal propensity to consume (=0.6, based on estimation using Family Income and Expenditure Survey in 2013–2017 (MIC 2018), and w is the input coefficient of wage per sector.

Employment inducement effects were evaluated using Eqs. (6)–(8), based on Hienuki and Hondo (2013).

$$L = l(I - A)^{-1}f + l(I - A)^{-1}Y \tag{6}$$

$$L_{\mathrm{d}} = l\left[I - \left(I - \widehat{M}\right)A\right]^{-1}(I - \widehat{M})f + l\left[I - \left(I - \widehat{M}\right)A\right]^{-1}Y_{\mathrm{d}} \tag{7}$$

$$L_{\mathrm{o}} = L - L_{\mathrm{d}} \tag{8}$$

where L represents the total employment inducement effect, L_{d} is the induced domestic employment, L_{o} is the induced overseas employment, and l is the input coefficient of labor per sector (diagonal matrix).

In this case, the saving of fertilizer costs by using food compost is reflected in the secondary effects because this saving results in an increase in the gross value added, including wages. The saving of food waste disposal costs for food services also increases the secondary effects, for the same reason. The cost calculation included consumptive goods, labor, and durable goods for on-site composting (composting machine). Only the composting machine was taken into consideration for the calculation because it fully serves for spinach cultivation and is not used to provide products to others.

2.5 Sensitivity analysis

For this study, we identified several key variables and assumptions and selected five key factors. A sensitivity analysis was then performed to examine the environmental/economic impacts of the key factors. Details of the factors are given in Table 3. These factors are selected owing to their high contribution to the total environmental impact in the specific impact category on any scenario (electricity consumption, energy recovery, N & P leaching, field GHG emission) or characteristic factor of closing "food-recycling loop" system (transportation distance).

3 Results and discussion

3.1 Environmental LCA

The results of simulation of field emission using the DNDC model indicated that N_2O emissions were 3.14 kg N_2O/ha in the CV scenario and 3.33 kg N_2O/ha in the CC/OC scenario. The difference between the scenarios was smaller; therefore, the emission factor per kilogram of nitrogen applied in the CC/OC scenario (0.72%) was smaller than in the CV scenario (1.21%). This can be

Table 3 Assumption of sensitivity analysis (CC: centralized composting, OC: on-site composting, CV: conventional)

Factors	Scenario	Description
Electricity consumption	CC, OC	Halve electricity consumption of centralized composting facility and composting machine
Energy recovery	CV	Introduce energy recovery (power generation, efficiency: 24.6%) in incineration facility
Transportation distance	All	Assume transportation distance 10 times longer than normal scenario. Distance from food service to composting facility (CC), farm (OC), incineration facility (CV), and from manufacturer of purchased organic fertilizer to farm (all scenarios) were considered
Field GHG emission	All	Decrease 30% of N_2O emission from field
N & P leaching	All	Decrease 30% of nitrogen and phosphorus leaching from field

Table 4 Environmental impact by scenario

Impact category	Unit	Centralized composting (CC)	On-site composting (OC)	Conventional (CV)
Climate change	kg CO_2eq/ha	4.74E+03	1.21E+04	4.38E+03
Acidification	kg SO_2/ha	3.15E+02	3.18E+02	2.25E+00
Ozone depletion	kg CFC11/ha	5.42E-05	3.98E-04	8.38E-05
Eutrophication	kg PO_4^{3-}eq/ha	1.35E+01	1.35E+01	7.41E+00
Resource depletion	kg Sb/ha	1.48E-02	5.29E-02	1.30E-02
Waste landfill	m^3/ha	1.18E-02	1.19E-02	2.37E+00

explained from empirical studies (Akiyama and Tsuruta 2003; He et al. 2019), which show that the N_2O emission factor per land area is negatively correlated with the C/N ratio of fertilizer. The C/N ratio of food waste compost in this study was 12, which is higher than that of market organic fertilizer with a C/N ratio of 4. Both simulated fertilizer-induced emission factors were higher than the value used in the Japanese GHG inventory, i.e., 0.62% (MoE and NIES 2019).

The characterized environmental load in six impact categories by scenario is listed in Table 4. The impact of climate change is the highest in the OC scenario, although this scenario reduces the impact of waste landfill by 96% compared with the CV scenario. Climate change impact is lowest in the CV scenario per ha of spinach production; however, it is lower in the CC scenario when considering the impact per kilogram of spinach production (0.529 kg CO_2eq/kg and 0.563 kg CO_2eq/kg for the CC and CV scenarios, respectively). Compared with the CV scenario, two impact categories are lower in the CC scenario in both functional units, while it is lower in four categories (other than acidification and eutrophication) per kg. All impacts of the OC scenario without waste landfill are higher than the CC scenario for both functional units.

Based on activity data, the fertilizer selection changed the fertilizer manufacturing process, and also the cultivation process, increasing the tillage and spreading of the fertilizer. The net substitution effect of market organic fertilizer can be calculated as follows: we avoided the impact of the fertilizer minus the increased impact in the new operation (Table 5). This estimation includes market organic fertilizer production, transportation, and energy use of additional farm operation (tillage). We excluded field emission because it can be highly changed by substitution (i.e., difference of form of nutrients and carbon) and also by total balance of nutrients in the soil.

In this case, the net substitution effect of climate change is 28.7% of the avoided impacts. For eutrophication and waste landfill, the net substitution effect is approximately 100% of the avoided impact because the change in operation mainly affects the GHG emission. This result suggests that agricultural practice should be considered when evaluating the effect of material recycling for agricultural use. For example, it is recommended that the avoided impact be examined in detail when evaluating bio-based regional material cycles. The methodology choice of substitution may strongly influence the results of an LCA, as stated by Hanserud et al. (2018). Additionally, the avoided impacts are usually calculated with the assumption that chemical fertilizer is substituted. The result of the net substitution effect should change in such cases.

Figure 3 indicates the environmental impact of each process per scenario. The main contributor of the CC and OC scenarios to climate change is the composting process, which consists of both direct and indirect emissions. Indirect emissions in the OC scenario are higher than in the CC scenario because the electricity consumption per composted material is much higher than the large-scale process. The composting process in the OC scenario consumes electricity for the stirring and deodorizing processes, as well as in the

Table 5 Net environmental effect by substituting market organic fertilizer by food waste compost

	Climate change (kg CO_2eq/ha)	Acidification (kg SO_2/ha)	Ozone depletion (kg CFC11/ha)	Eutrophication (kg PO_4^{3-}eq/ha)	Resource depletion (kg Sb/ha)	Waste landfill (m^3/ha)
Market organic fertilizer (A)	− 1.05E+02	− 2.55E+01	− 1.34E-04	− 2.68E-07	− 8.30E+01	− 1.00E-04
Transportation of input materials (B)	− 7.46E+00	− 1.12E+00	5.21E-08	1.08E-10	− 6.42E+00	7.82E-12
Farm machinery operation (C)	8.24E+01	1.20E+01	9.64E-07	1.92E-09	7.68E+01	1.45E-10
Net substitution effect 1 (A+B+C)	− 3.01E+01	− 1.47E+01	− 1.33E-04	− 2.66E-07	− 1.27E+01	− 1.00E-04
(A+B+C)/(A)	28.7%	57.4%	99.2%	99.2%	15.3%	100.0%

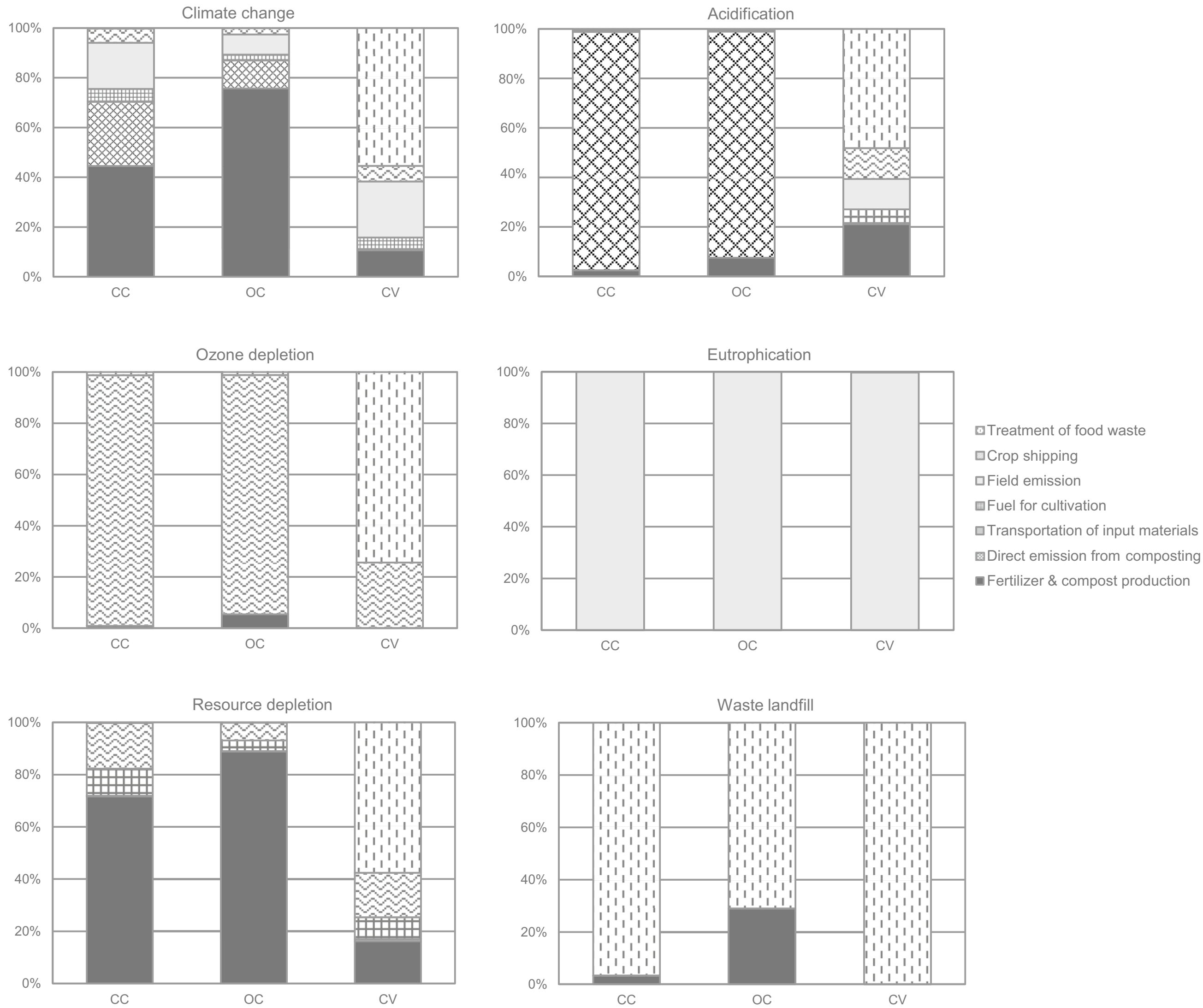

Fig. 3 Contribution of processes by impact categories (CC: centralized composting, OC: on-site composting, CV: conventional)

drying process, which uses the residual heat of deodorizing. Heating energy appears to be the main reason for the difference in energy consumption. In the CV scenario, more than 60% of GHGs are derived from the waste treatment process, and particularly from N_2O emissions in waste combustion and from energy use in the incineration plant. Direct emission from the composting process is critical in acidification, which contributes a higher impact in the CC and OC scenarios. Almost all (> 99.9%) eutrophication impacts were caused by field emissions (nitrogen and phosphorus leaching from the agricultural field). Food waste is the main source of waste in the landfill for the CV scenario, while the volume of the landfill was reduced by incineration. There is a significant difference between the CV scenario and the other scenarios in terms of the volume of the waste landfill because only composting residue is incinerated and landfilled in the composting process of the CC and OC scenarios.

Figure 4 a illustrates the weighted environmental impacts by scenario with different functional units. The price of spinach is assumed to be 500 JPY/kg, and the weighted environmental impacts were estimated as 0.86–1.61% of the economic value. Acidification, climate change, and waste landfill contribute most critically to the total environmental impact (48%, 49%, and 75%, respectively). Not surprisingly, the environmental impact will decrease when food waste is composted, even if only decentralized composting is introduced. The CC and OC scenarios reduced the weighted impact per 1 kg of spinach by 47% and 17%, respectively. Although the unit yield of the CV scenario was 15% lower than that of all other scenarios, the trend of environmental impact per area is similar to that per weight.

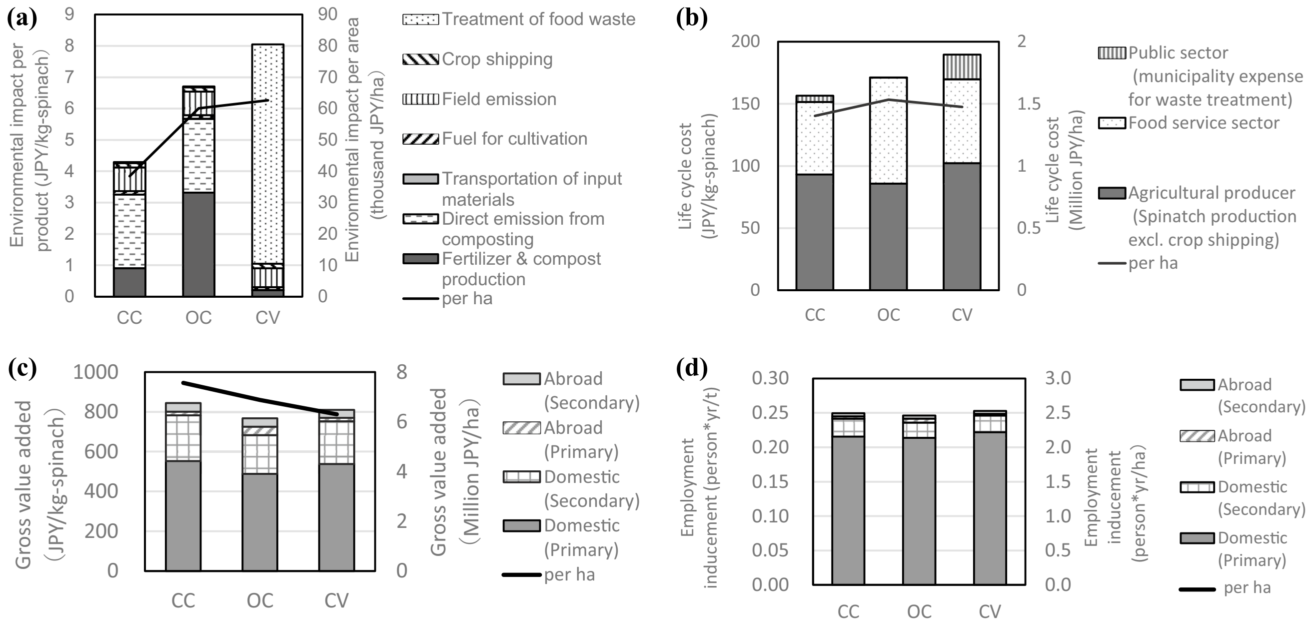

Fig. 4 Environmental and economic impact by scenario; (**a**) weighted environmental impact, (**b**) life cycle cost, (**c**) gross value added, and (**d**) employment inducement. CC: centralized composting, OC: on-site composting, CV: conventional

3.2 Socio-economic assessment

The life cycle cost of spinach cultivation and waste management is shown in Fig. 4b, stacked by stakeholders. In this figure, the life cycle cost is calculated as the difference in the public sector (local government) expenses between the waste treatment fee and the actual treatment cost in the CC and CV scenarios. The food service sector (generator of food waste) pays a waste treatment fee to the local government in CC and CV scenarios, while in the OC scenario, a transportation and composting machine (including electricity) fee is paid. Compost in the OC scenario is provided to farmers for free, while in the CC scenario, it is assumed to be sold at 5000 JPY/t. The product weight-based life cycle cost in the CC and OC scenarios is almost equal. However, it is slightly higher in the CV scenario because food waste treatment is required. There are no significant differences in the land area-based life cycle cost for the scenarios. The expenses of the food service sector increase in the OC scenario; however, these expenses may be reduced if the compost price is set. The expenses of local government and farmers may also decrease if a food waste composting system is developed.

The difference in the weight-based induced gross value added among the scenarios is not significant (Fig. 4c). The estimated values are 844 JPY/kg in the CC scenario, 767 JPY/kg in the OC scenario, and 810 JPY/kg in the CV scenario. The contributed affect to abroad is more pronounced in the OC scenario than for the other scenarios, mainly due to electricity use and machine production, which are highly dependent on fuel and ore import. This also results in a slightly reduced contribution to the local economy. Area-based induced gross value added is lowest in the CV scenario. When focusing on land use and agricultural practices, higher inputs of food waste compost to fields improve the economic ripple effect. As shown in Fig. 4d, the CV scenario creates most employment per kg of spinach production. Approximately 97% of employment is sourced domestically in all the scenarios. Employment for the agricultural sector, including spinach production, is responsible for 84–86% of total employment (primary and secondary). This reflects the high ratio of locally sourced employment.

Tables 6 and 7 show a breakdown of the economic effect on 13 economic sectors. Here, 42–47% of the gross value added is from the agricultural sector, including both primary and secondary effects. The impact to the service sector in the CV scenario is higher than for the other scenarios because this sector contains waste treatment, in contrast to the centralized composting process used by the agricultural, forestry, and fishery sectors. The impact of employment on the sectors, with the exception of the agricultural sector, is not as significant as the impact of the gross value added.

Existing research evaluating the economic effects of food waste recycling on a national level in Japan (Ozeki

Table 6 Gross value added of 13 sectors by scenario (unit: JPY/kg-spinach)

	Centralized composting (CC)	On-site composting (OC)	Conventional (CV)
Agriculture, forestry and fishery	480	460	446
Mining	15	21	13
Manufacturing	56	71	55
Construction	5	4	3
Electricity, gas and water supply	7	15	7
Commerce	46	45	45
Finance and insurance	18	18	18
Real estate	54	49	51
Transport and postal services	39	20	21
Information and communications	16	15	16
Public administration	5	5	1
Services	102	43	131
Activities not elsewhere classified	2	2	1
Total	844	767	810

2003) reported that changes in the gross domestic product (GDP) and induced production are highly limited, less than 0.1%, although changes to organic and chemical fertilizer production, as well as to waste management, were significant (over 20%). The study focused on the recycling system and the scope is limited. However, their results are consistent with this study.

3.3 Sensitivity analysis

The sensitivity of the key factors is summarized in Tables 8 and 9. The energy-related factors (electricity consumption and energy recovery introduction) are significant contributors to climate change and resource depletion in the OC and CV scenarios. Life cycle GHG emission of the CV scenario is lower than for the normal CC scenario when thermal energy is recovered in both functional units. The reduction of field emissions (GHG and N&P leaching) results in a drastic decrease in corresponding impact categories, thereby impacting each category significantly. Most of the sensitivity to socio-economic indicators are very limited; however, some tradeoffs and synergy effects can be observed. Energy recovery will reduce the environmental impact of incineration and marginally improve socio-economic indicators to some extent due to additional energy production. The longer transportation

Table 7 Employment inducement effect of 13 sectors by scenario (unit: person*yr/t)

	Centralized composting (CC)	On-site composting (OC)	Conventional (CV)
Agriculture, forestry and fishery	0.212	0.211	0.212
Mining	0.000	0.001	0.000
Manufacturing	0.006	0.007	0.007
Construction	0.001	0.001	0.001
Electricity, gas and water supply	0.000	0.001	0.000
Commerce	0.008	0.008	0.008
Finance and insurance	0.001	0.001	0.001
Real estate	0.001	0.001	0.001
Transport and postal services	0.006	0.003	0.003
Information and communications	0.001	0.001	0.001
Public administration	0.000	0.000	0.000
Services	0.012	0.012	0.019
Activities not elsewhere classified	0.000	0.000	0.000
Total	0.250	0.246	0.253

Table 8 Result of sensitivity analysis: change of environmental load by scenario (CC: centralized composting, OC: on-site composting, CV: conventional)

		Electricity consumption	Energy recovery	Transportation distance	Field GHG emission	N & P leaching
Climate change (kg CO_2eq/ha)	CC	− 3.8% (− 2.2E+02)	-	+7.0% (3.2E+02)	− 5.6% (− 3.0E+02)	0.0% (0)
	OC	− 15.1% (− 2.0E+03)	-	+0.9% (1.2E+02)	− 2.4% (− 3.0E+02)	0.0% (0)
	CV	-	− 37.7% (− 1.7E+03)	+4.1% (1.8E+02)	− 6.8% (− 2.8E+02)	0.0% (0)
Acidification (kg SO_2/ha)	CC	− 0.2% (− 8.5E-02)	-	+1.5% (1.8E+00)	0.0% (0)	0.0% (0)
	OC	− 1.5% (− 9.1E-01)	-	+0.1% (3.2E-02)	0.0% (0)	0.0% (0)
	CV	-	− 39.8% (− 6.6E-01)	+4.8% (− 5.2E-01)	0.0% (0)	0.0% (0)
Ozone depletion (kg CFC11/ha)	CC	− 0.1% (− 8.0E-06)	-	0.0% (0)	0.0% (0)	0.0% (0)
	OC	− 1.1% (− 7.8E-05)	-	0.0% (0)	0.0% (0)	0.0% (0)
	CV	-	− 0.3% (− 6.1E-05)	0.0% (0)	0.0% (0)	0.0% (0)
Eutrophication (kg PO_4^{3-}eq/ha)	CC	0.0% (0)	-	0.0% (0)	0.0% (0)	− 30.0% (− 4.0E+00)
	OC	0.0% (0)	-	0.0% (0)	0.0% (0)	− 30.0% (− 4.0E+00)
	CV	-	0.0% (0)	0.0% (0)	0.0% (0)	− 29.9% (− 2.2E+00)
Resource depletion (kg Sb/ha)	CC	− 4.5% (− 9.9E-04)	-	+14.1% (1.7E-03)	0.0% (0)	0.0% (0)
	OC	− 17.8% (− 9.9E-03)	-	+1.7% (5.3E-04)	0.0% (0)	0.0% (0)
	CV	-	− 38.7% (− 7.6E-03)	+7.3% (8.0E-04)	0.0% (0)	0.0% (0)
Waste landfill (m^3/ha)	CC	0.0% (0)	-	0.0% (0)	0.0% (0)	0.0% (0)
	OC	− 5.8% (− 8.5E-05)	-	0.0% (0)	0.0% (0)	0.0% (0)
	CV	-	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)

distance in the CC scenario increases GHG emissions. In contrast, it will improve employment inducement as it promotes the demand of waste collection and transportation services which are relatively labor-intensive industries. From the perspective of planning, transportation distance is also related to the collection area of food waste, which is a factor of the quantitative potential of food waste recycling. Therefore, the environmental impact reduction potential of composting facilities may increase when the environmental load per weight increases due to longer transportation. Alternatively, it is recommended that the OC scenario completes its system in smaller urban areas where centralized facilities cannot be installed nearby, for both environmental and socio-economic aspects.

4 Conclusion

It is important to support the system of "3R" for food waste processing by accumulating scientific knowledge and developing reliable decision-making measures. An LCA focusing on both food waste treatment and a vegetable cultivation system was performed in this study. The development of an on-site centralized composting system reduces the total environmental impact by reducing landfill waste, although there is a tradeoff between landfill waste and GHG emissions when using an on-site composting system. In addition, a composting system is feasible from an environmental and socio-economic perspective when compared with conventional organic production because

Table 9 Result of sensitivity analysis: change of economic effect by scenario (CC: centralized composting, OC: on-site composting, CV: conventional)

		Electricity consumption	Energy recovery	Transportation distance	Field GHG emission	N & P leaching
Gross value added	CC	− 0.0%	-	+0.3%	0.0%	0.0%
	OC	− 0.1%	-	+0.0%	0.0%	0.0%
	CV	–	+0.1%	+0.0%	0.0%	0.0%
Employment inducement	CC	− 0.1%	-	− 1.0%	0.0%	0.0%
	OC	+0.1%	-	− 1.3%	0.0%	0.0%
	CV	-	+0.1%	0.0%	0.0%	0.0%

the economic ripple effect is slightly negative or positive. The OC scenario needs to reduce the amount or emission factor of electricity used to improve the environmental competitiveness with the CV scenario. These results should be applicable to any urban and peri-urban area in other countries, especially in high population countries where the impact of waste landfills is relatively high. Further, our results demonstrated that the substitution effect of recycled compost may be partly reversed with the implementation of minor changes to agricultural practices. This suggests that the net substitution effect is smaller than assumed in the recycling LCA. Thus, it is recommended to consider whether the agricultural operation would be changed with the substitution effect of composting. Further research should measure the substitution effect from chemical fertilizer, which was not covered in this study of an organic farm.

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