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Research article

Assessment of new functional units for agrivoltaic systems

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ABSTRACT

In agrivoltaic systems, photovoltaic (PV) modules are ground-mounted between crops replacing a part of greenhouse or are set below or above the cover film of greenhouse; these can provide solutions with respect to land competition and climate change mitigation. These systems have certain additional functions, namely, sunlight sharing, land sharing and power generation, as compared to the conventional agricultural production systems. These new functions are not adequately performed by traditionally used functional units (FUs), such as the mass- or the area-based FU, in agricultural life cycle assessment (LCA). Therefore, this study proposed new FUs for agrivoltaic systems, namely the modified area-based FU and the monetary-based FU. The modified area-based FU was derived by adding area covered by PV modules to the cultivated area addressing the function of land sharing. The monetary-based FU was derived by adding the prices of crops and electricity addressing the function of the system as a producer of differently valued market goods. The traditional area-based FU is based on the function of solar sharing because crop cultivation and power generation share the same sunlight falling on the same land. These new and traditional FUs were applied to a tomato greenhouse, with and without organic photovoltaics, as a case study of Japan. A combination of traditional and new FUs helps to maintain focus on crop production as the primary function of agricultural land and to better understand the environmental impacts of agrivoltaic systems. Finally, as the sharing of sunlight and land happen simultaneously, a method that addresses both these functions while reporting LCA results was considered.

1. Introduction

The world must combat climate change while meeting the food demands of the fast growing world population (FAO, 2012). Greenhouses, with or without heating systems and long-distance transportation, have resulted in year-round food production across the world; however, they have also resulted in increasing CO_2 emissions. The heating in greenhouses accounts for a large portion of the total life-cycle CO_2 (LC-CO_2) emissions. The CO_2 emissions from fossil fuel consumption and cement production has increased more rapidly since 2000 than in the 1990s (Ciais et al., 2013). The atmospheric concentration of CO_2 has increased by 40% since 1750 and reportedly reached 391 ppm in 2011 (Ciais et al., 2013). The average world temperature has increased by 0.85 °C since 1880.

Replacing fossil fuels with renewable energy sources is an important global climate change mitigation option. By 2015, 164 countries had set at least one renewable energy target (International Renewable Energy Agency, 2015). However, one challenge in meeting such targets is the allocation of land. Production of dedicated bioenergy crops competes with that of food crops, and is recommended on abandoned land (Zumkehr and Campbell, 2013). Solar PV panels require lesser land than biodiesel and biomass-based power generation systems for the same power output (McDonald et al., 2009). However, land-based PV farms compete with bioenergy production for land allocation. Thus, roof-top PV and agrivoltaic systems are becoming increasingly relevant. An agrivoltaic system is one in which sunlight over a piece of land is shared for crop production and power generation by PV technology. Calvert and Mabee (2015) concluded that the roof top solar PV technologies could be a solution to the competition for land between the land-based solar PV units and dedicated bioenergy crops. Dupraz et al. (2011) predicts that with the use of the agrivoltaic system, global land productivity will increase by 35–73%. Further, Dinesh and Pearce (2016) reported an increase in economic value by more than 30% when power generation was coupled with cultivation of shade tolerant crops. Although PVs interfere with crop growth and yields of agricultural crops due to increase in shade, the level of interference may vary with the arrangement of PVs and crops. While rice (Homma et al., 2016) and lettuce (Marrou et al., 2013) yields were reduced due to increase in shade, tomato yield was not (Ureña-Sánchez et al., 2012).

Life cycle assessment (LCA) is one of the primary methods to

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evaluate environmental impacts of products and services. The agrivoltaic system has certain additional functions, namely sunlight sharing, land sharing and power generation, as compared to conventional agricultural production systems. Thus, LCA should be conducted in a way that addresses the unique functions of the agrivoltaic system. Special attention needs to be paid to the choice of functional unit (FU), which, in turn, is related to the reporting of LCA results. The FU is defined based on the goal of a study. It normalizes environmental impacts and allows for comparison between the environmental impacts of different systems. Most agricultural LCAs choose mass, energy, protein contents, area or unit of livestock, as FU (Roy et al., 2009). The FUs based on annual or daily intake, or aggregated nutritional quality (represented by indices), are suitable for comparing food item, meal, and diet (the meal and the diet are the consumption of collection of the food items by individual and by whole population, respectively, Heller et al., 2013). An area-based FU reflects the function of an agricultural system as a producer of non-market goods (e.g. environmental service; as stated by Basset-Mens and van der Werf, 2005). It is suitable for landscape management and minimization of fertilization intensity (de Backer et al., 2009). Cherubini (2010) suggested using area-based FUs, along with other FUs (e.g. per vehicle, on km basis), in a bioenergy system, to express relative efficiencies in greenhouse gas reduction from dedicated biomass production when compared to other land uses, as dedicated biomass production competes with other agricultural activities. A mass-based FU reflects the function of an agricultural production system as a producer of market goods (Basset-Mens and van der Werf, 2005). Mass-or volume-based FUs (with or without quality corrections) are suitable choices for comparison of production methods and for hotspot analyses (Heller et al., 2013). Because the choice of FU influences LCA results, this choice remains a methodological aspect that requires further improvement (Notarnicola et al., 2017). It is particularly crucial when comparing systems with different yields per unit area, for instance, organic and conventional farming (Basset-Mens and van der Werf, 2005). Salou et al. (2017) argued that a single FU is not adequate for sound decision making. Reporting LCA results based on multiple FUs is recommended for a better understanding of environmental impacts, although each FU reflects different functions of agricultural production systems (Roy et al., 2009).

The FUs used in previous studies did not adequately address the functions unique to an agrivoltaic system, namely sunlight sharing, land sharing, and power generation. The aim of this study, therefore, is to propose two new FUs for an agrivoltaic system: modified area-based FU and monetary-based FU. The new and the traditional FUs (i.e. mass-and area-based FUs) are applied to a tomato greenhouse, with and without organic photovoltaics (OPV), as a case study of Japan. The present study focuses on LC-CO_2 emissions with an aim to propose new FUs for agrivoltaic systems that can be applied to other environmental impact categories.

2. Material and methods

2.1. Goal, scope, system boundary, and functional unit

The LCA is carried out with reference to the International Organization for Standardization (ISO) 14040 (2006a) and 14044 (2006b) guidelines and the methodological guidelines for PV LCA (Frischknecht et al., 2015). Its aim is to compare LC-CO_2 emissions between an agrivoltaic system and a conventional system in the case of production of tomatoes. The system boundary is limited from cradle to gate for crop production, and from module production to use phase for OPV (Fig. 1). The present study leaves the end-of-life stage for future research, as a few previous studies (i.e. Søndergaard et al., 2014, Espinosa et al., 2015 and Tsang et al., 2016) have included the whole system. The new (modified area-based and monetary-based) and the traditional (i.e. mass-and area-based) FUs are used to report the LCA results.

2.2. Two new functional units

2.2.1. Modified area-based FU

The present study proposed a modified area-based FU to address the aspect of land sharing. The underlying idea of this FU was from a study by Kovacic et al. (2018) — it is an LCA study related to a building, where energy consumptions and global warming potentials are defined based on either gross floor area or net floor area. The agrivoltaic systems do not require extra land for power generation, because PV modules are ground-mounted between crops, replacing a section of greenhouse or are set below or above the cover film of greenhouse as a two-storied building: One floor for crop production and another floor for power generation. As yet, the idea of gross or net floor has not been used in the LCA studies related to agriculture, to the best of our knowledge.

This FU is obtained by summing up area covered by PV modules and cultivation. In the present study, the area covered by OPV was 66 m^2 and the cultivated area was 162 m^2; therefore, the areas covered in the agrivoltaic system and the conventional system is 228 (66 + 162) m^2 and 162 m^2, respectively.

2.2.2. Monetary-based FU

The monetary-based FU is derived by adding prices of crop and generated power. The price of a crop is obtained from the 10-year average of its wholesale price (Ministry of Agriculture, Forestry and Fisheries: MAFF, 2017). The price of power is derived from the price of electricity (25 yen/kWh, as per the Agency for Natural Resources and Energy, 2016). In the present study, it was assumed that the power generated by OPV was used by the farmer on the field.

2.3. Life cycle inventory

The OPV modules arrangement, referred to as the Kizu Experimental Farm (long 135.8369°, lat 34.7339°), was established at the Kyoto University; the monitoring was conducted in a greenhouse, with and without OPV. The frontage, depth and ridge height of each house was 9 m, 18 m, and 5.18 m, respectively. The OPV sheets were set on the roof and the walls of the greenhouse – 25 sheets each, on the east and the west roof; 12 sheets each, on the east and the west wall, and 6 sheets each, on the north and the south gable (Fig. 2, Leon and Ishihara, 2018). The OPV modules were installed inside the greenhouse. Further, eight inverters, each with a capacity of 300 W_p, were installed.

The inventory analysis was carried out using the inventory database, 'Inventory Database for Lifecycle Analysis' (IDEA ver. 2, National Institute of Advanced Industrial Science and Technology (AIST) and Japan Environmental Management Association for Industry (JEMAI)). Due to lack of data, inventory data on the inverters were obtained from Ecoinvent ver. 3. The energy mix for Japan for 2014 was 0.606 kg-eqCO_2/kWh. Nitrous oxide (N_2O) emissions were estimated following Pluimers et al. (2000).

Global warming potential (GWP) was calculated using the MiLCA ver. 2 software, equipped with IDEA ver. 2. A time horizon of 100 years was used for this purpose.

2.4. Tomato production

Inventory data for tomato production were obtained from the experimental greenhouse at the Kyoto University. Table 1 shows the total inputs of the case tomato greenhouse. For both the agrivoltaic and the conventional systems, tomatoes were double-cropped, leaving the land fallow after harvesting. Seeding started in July 2016 or in March 2017, and the transplanting was completed in September 2016 or in May 2017, respectively. Thereafter, the harvesting started from the middle of October to the end of February for the autumn-winter cultivation period, and from the end of June to the beginning of August for the spring-summer cultivation period. A hydroponics system with a soil-less

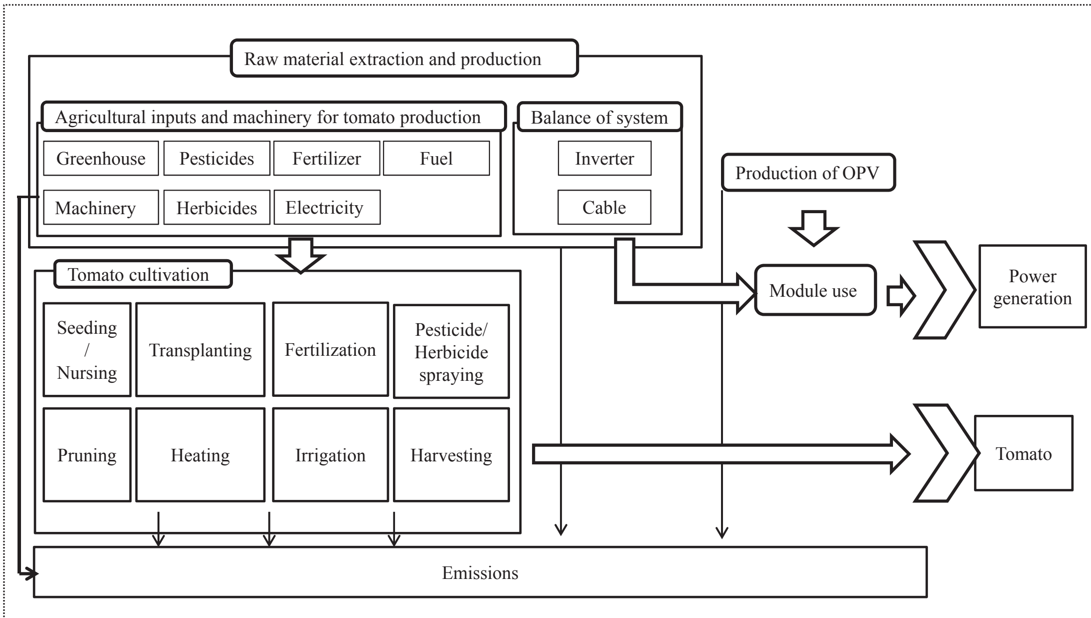

Fig. 1. System boundary of agrivoltaic system for the present case study.

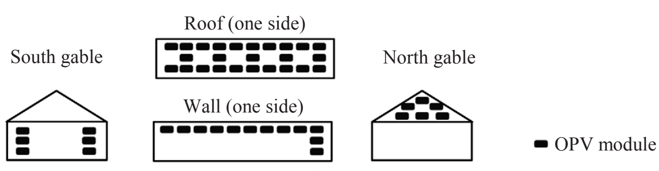

Fig. 2. The arrangement of OPV modules in the experimental greenhouse for the present case study.

media of rock-wool was used. Equal amount of pesticides was applied to the agrivoltaic and conventional systems. The setting temperature of the heater was 12 °C. Heating was done from 15 November 2016 to 20 February 2017.

2.5. OPV production and power generation from them

The OPV modules (a model specification is KMM1015E3F) introduced into the greenhouse were produced by the Mitsubishi Chemical Co. (by employing roll-to-roll methods and sealed by polyethylene terephthalate). The specification of the OPV module was, as follows: maximum output (18 W), power convergent efficiency (2.7%), active area (470 mm × 1489 mm) and module size (500 mm × 1537 mm). Since the details regarding the materials used and the production process are to be kept confidential, the present study cited an LCA study by Espinosa et al. (2011) for the data on the amount of embodied CO_2 required in manufacturing 1 square meter of OPV: it is 15.49 kg eq-CO_2 m^{-2}. The lifespan of the module and the inverter was assumed to be 10 years. The power generated by the OPV was estimated to be 1025 kWh, using the following values: the maximum power rating of OPV i.e., 18 W, average temperature coefficient as 0.85, temperature rise coefficient as 0.98, conversion efficiency of inverter as 0.96, and coefficient for the other losses as 0.95. Further, the average annual irradiance values were, as follows: 3.42 kWh $m^{-2}d^{-1}$ for east and west roof with tilt angle of 26.6°, 2.07 kWh $m^{-2}d^{-1}$ for east and west walls, 2.48 kWh $m^{-2}d^{-1}$ for south wall and 1.19 kWh $m^{-2}d^{-1}$ for north wall (New Energy and Industrial Technology Development Organization (NEDO)); the solar transmittance value of the covering films was taken as 0.86. The embodied CO_2 to produce OPV and inverter & the power generated by the OPV per greenhouse (of 162 m^2 area) per year was estimated at 102.4 kg-eq CO_2, 36.3 kg-eq CO_2 and 1025 kWh, respectively. The emission factor was estimated at 0.14 kg-eq CO_2/kWh.

2.6. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the influence of choice of OPV-related LCA studies on the LCA results; these studies had varying embodied LC-CO_2 emissions and OPV lifetime. Out of the 15 papers (11 of them are listed by Chatzisideris et al. (2016) and four other references: Roes et al. (2009), García-Valverde et al. (2010), Espinosa et al. (2011), Emmott et al. (2012), Espinosa et al. (2012a), Espinosa et al. (2012b), Yue et al. (2012), Anctil et al. (2013), Espinosa et al. (2013), Espinosa et al. (2014), Espinosa and Krebs (2014), Søndergaard et al. (2014), Espinosa et al. (2015), Tsang et al. (2015), Tsang et al. (2016)), five were selected that had data on CO_2 emissions required to fabricate 1 m^2 of OPV and the lifetime of OPV. The LC-CO_2 emissions and lifetime are summarized in Table 2.

3. Results

3.1. Fertilizer requirement, electricity consumption in heating and yield

As shown in Table 1, the application rate of fertilizer differed slightly between the agrivoltaic and the conventional systems. The electricity consumption for heating in the agrivoltaic system was lower (30 kWh) than in the conventional system. However, the yield of tomatoes was reduced by 9% in the agrivoltaic system (1513 kg in the agrivoltaic system and 1669 kg in the conventional system).

3.2. LC-CO_2 emissions defined by the traditional and new functional units

LC-CO_2 emissions in the agrivoltaic and conventional systems are summarized in Table 3. The total LC-CO_2 emissions in the agrivoltaic system were lower in comparison to the conventional system for both the area-based and the mass-based FUs, (traditional FUs), due to the LC-CO_2 emission reduction in the power generation. Similar results were obtained on using the new, proposed FUs (i.e. modified area- and monetary-based).

However, the LC-CO_2 emissions in the agrivoltaic system in the case of mass-based and monetary-based FUs were only marginally lower as

Table 1
Total quantity of inputs of the case tomato greenhouse (per 162 m^2 of greenhouse).

		Unit	Input
Greenhouse construction	Concrete	m^3	0.09
	Crushed rock	kg	96.00
	Rebar	kg	5.63
	Bolt and nut	kg	0.65
	Welded wire mesh	kg	1.12
	Diesel	litter	1.20
	Shaped steel	kg	44.60
	Hot rolled steel	kg	27.15
	Zinc coat	kg	40.06
	Aluminium bars	kg	0.97
	Aluminium extraction products	kg	12.40
	Aluminium plates	kg	0.40
	Aluminium window frame	kg	1.20
	Aluminium door	kg	2.67
	Steel wire	kg	0.71
	Steel pipe	kg	110.00
	Steel	kg	58.00
	Switchgears, switchboards, and electrical control equipment	Yen	397,742
	Fluorinated resin	kg	4.08
	Low density polyethylene	kg	10.50
	Polyethylene	kg	11.23
	Aluminium deposited film	m^2	55.20
	Polyester	kg	3.20
	Heater	Yen	214,286
	Expanded polystyrene	kg	9.70
	Zinc plated steel sheet	kg	1.90
	Pump	Yen	68,500
	High density polyethylene	kg	6.87
	Steel, chromium steel	kg	0.98
	Copper	kg	0.12
	Vinyl chloride	kg	4.00
Tomato cultivation	N (Conventional house)	kg	7.27
	P_2O_5 (Conventional house)	kg	3.56
	K_2O (Conventional house)	kg	11.13
	N (OPV house)	kg	6.21
	P_2O_5 (OPV house)	kg	3.09
	K_2O (OPV house)	kg	9.55
	Polystyrene	kg	0.06
	Peat moss	kg	1.09
	Vermiculite	kg	0.52
	Other lime product	Yen	7.02
	Single superphosphate	kg	0.01
	Low density polyethylene	kg	3.98
	Rockwool	kg	95.10
	Other pesticide	kg	0.30
	Fungicide	kg	0.90
	Insecticide	kg	1.90
	Herbicide	kg	0.30
	Polyethylene	kg	3.63
	Aluminium deposited film	m^2	30.00
	Electricity (Conventional house)	kWh	3208
	Electricity (OPV house)	kWh	3178

Table 2
Embodied CO_2 emissions and lifetime of OPV in OPV-related LCA studies.

References	CO_2 emission (kg-CO_2/m^2)	Lifetime
García-Valverde et al. (2010)	112.03	15
Espinosa et al. (2012a)	20.66	15
Espinosa et al. (2013)	2.35, 3.22, 3.44	15
Espinosa et al. (2014)	2.94	1
Espinosa and Krebs (2014)	1.36	1

compared to that in the conventional system due to the negative influence of OPV on tomato yield. This difference would have been reduced or disappeared if the power generation was reduced further, or if LC-CO_2 emissions from tomato production or from fabricating OPV and inverters, vary, as detailed in the sensitivity analysis.

3.3. Sensitivity analysis

A sensitivity analysis was carried out to examine the influence of embodied CO_2 and lifetime of OPV on LC-CO_2 emissions (Table 4). The LC-CO_2 emissions were estimated to be in the range 2.6–2.9 kg-eq CO_2 per kg of tomato production for the mass-based FU, 24.4 and 27.4kg-eq CO_2 per m^2 for the area-based FU, 17.3 and 19.4 kg-eq CO_2 per m^2 for the modified area-based FU, and 7.86 E-03 and 8.82 E-03 kg-eq CO_2 per yen for the monetary-based FU. The LC-CO_2 emissions based on the mass-based and monetary-based FUs in the agrivoltaic system were larger as compared to corresponding values for the conventional system in the case of OPV study reported by García-Valverde et al. (2010). For the other OPV studies, the LC-CO_2 emissions in the agrivoltaic system were lower as compared to that in the conventional system. The choice of LCA study is particularly important when the mass-based or monetary-based FU is chosen, because these FU are influenced by crop yield reduction, which is attributed to the interference in crop growth and reduction in yields of agricultural crops due to the shade effect by the PVs.

4. Discussion

4.1. The new functional unit

In this study, new functions unique to the agrivoltaic system, namely sunlight sharing, land sharing and power generation, have been added over and above the functions of the conventional agricultural production systems. Several previous LCA studies related to agriculture used mass, energy and protein contents, and area or unit of livestock as FUs (Roy et al., 2009). In the agrivoltaic system, the area-based FU is used to reflect the function of agricultural production systems as a producer of non-market goods (for instance, environmental service; as in Basset-Mens and van der Werf, 2005), and of solar sharing because the same sunlight is shared by crop cultivation and power generation on the same land. It is also used for landscape management and minimization of fertilization intensity. However, the area-based FU and the other FUs used in the previous studies did not adequately address the functions unique to the agrivoltaic system. For example, although roof top PV and agrivoltaic systems have become increasingly important as solutions to land competition and the benefits of using an agrivoltaic system has been reported by Dupraz et al. (2011) and Dinesh and Pearce (2016), no FU can describe the environmental load in terms of the land sharing with respect to land use efficiency. To address the function of land sharing, the present study proposed a modified area-based FU. This FU can be used to express efficiency in environmental load reduction in comparison with the conventional system. In the present study, when a modified area-based FU was used, the LC-CO_2 emission was 17.7 kg-eq CO_2 under the agrivoltaic system and 28.1 kg-eq CO_2 under the conventional system.

Monetary-based FU addresses the function of agrivoltaic systems as a producer of market goods (i.e., crops and electricity). The mass-based FU focuses only on crop production, but the monetary-based FU accounts for the differently valued market goods. However, as in the case of a mass-based FU, the environmental load of agrivoltaic systems using monetary-based FU is only marginally lower than that of conventional systems, as has been discussed in section 3.2.

4.2. The choice of functional unit

As in the organic farming system (de Backer et al., 2009; Blengini and Busto, 2009), special caution needs to be exercised in the agrivoltaic system in choosing FU, as it compares systems with different yields per unit area (Basset-Mens and van der Werf, 2005). One time use of the area-based and modified area-based FU would not reveal the yield reduction, which is addressed by the mass-based FU or possibly by the monetary-based FU. In contrast, single use of the mass-based and

Table 3
LC-CO_2 emissions in the agrivoltaic and conventional systems based on old and new functional units.

		Agrivoltaic system				Conventional system
		Tomato production	Fabricating OPV and inverters	LC-CO_2 reduction by power generation	Total LC-CO_2 emissions	Total LC-CO_2 emissions
		A	B	C	A + B-C	
Traditional FU	Mass-based FU (kg-eq CO_2 per kg of tomatoes)	2.989	0.092	0.411	2.67	2.73
	Area-based FU (kg-eq CO_2 per m^2)	27.91	0.86	3.83	24.9	28.1
New FU	Monetary-based FU[a] (kg-eq CO_2 per yen)	9.004E-03	2.761E-04	1.237E-03	8.04E-03	8.65E-03
	Modified area-based FU[b] (kg-eq CO_2 per m^2)	19.83	0.61	2.72	17.7	28.1

[a] Monetary-based FU: The price for the FU is derived from the sum of prices of tomato and electricity.
[b] Modified area-based FU: The area for the FU is derived from the sum of cultivated area and area covered by OPV: 228 m^2 in the agrivoltaic system and 162 m^2 in the conventional system.

Table 4
Influence of choice of LCA studies related to OPV on LC-CO_2 emissions.

	Mass-based FU		Area-based FU		Modified area-based FU		Monetary-based FU	
	Agri[a]	Conv[b]	Agri	Conv	Agri	Conv	Agri	Conv
Current study (Espinosa et al., 2011)	2.7	2.7	24.9	28.1	17.7	28.1	8.04E-03	8.65E-03
García-Valverde et al. (2010)	2.9	2.7	27.4	28.1	19.4	28.1	8.82E-03	8.65E-03
Espinosa et al. (2012a)	2.7	2.7	24.9	28.1	17.7	28.1	8.02E-03	8.65E-03
Espinosa et al. (2013)	2.6	2.7	24.4	28.1	17.3	28.1	7.86E-03	8.65E-03
Espinosa et al. (2013)	2.6	2.7	24.4	28.1	17.3	28.1	7.87E-03	8.65E-03
Espinosa et al. (2013)	2.6	2.7	24.4	28.1	17.3	28.1	7.87E-03	8.65E-03
Espinosa et al. (2014)	2.7	2.7	25.4	28.1	18.0	28.1	8.19E-03	8.65E-03
Espinosa and Krebs (2014)	2.7	2.7	24.9	28.1	17.7	28.1	8.02E-03	8.65E-03

[a] Agri: Agrivoltaic system.
[b] Conv: Conventional system.

the monetary-based FU will fail to take into account the agricultural intensification (e.g. fertilization intensity, de Backer et al., 2009) in case yield per area increases, which may influence sustainable food production. Agricultural intensification can be undertaken under the agrivoltaic system to compensate for yield reduction. Most recently, Salou et al. (2017) critically noted that a singular use of mass-based FU will ignore the environmental impact caused by agricultural intensification (increase in agricultural products per input, like the land area; it is touted to be one of the methods employed to meet the needs of world's growing population). To avoid this, the authors recommended that the environmental impacts be analysed using both area-based and mass-based FUs, because the area-based FU takes the intensification of the agricultural system into account. Reporting LCA results based on multiple FUs was recommended for a better understanding of environmental impacts, although each FU reflects different functions of agricultural production systems (Roy et al., 2009). Therefore, in the present study, a combination of traditional and new FUs has been employed in the agrivoltaic system that help maintain focus on crop production as the main function of agricultural land. This will also contribute towards sustainable food production.

4.3. A method to present environmental impacts addressing sunlight and land sharing simultaneously

The earlier studies that discussed the choice of FU did not adequately touch upon how to present the environmental impacts while using several functions simultaneously. Because sunlight and land sharing happens simultaneously, a method to address both functions is required in the reporting of LCA results. One such method is presented, as follows: it is assumed that the environmental impacts comprised two parts: weighted sunlight sharing and weighted light sharing (eq. (1)).

$$\eta \mathrm{LC}-\mathrm{CO_2(S)} + (1-\eta)\mathrm{LC}-\mathrm{CO_2(L)} \quad (1)$$

Where η is the weight derived as a ratio of sunlight use (eq. (2)); LC-CO_2 (S) and LC-CO_2 (L) represent the LC-CO_2 emissions obtained based on sunlight sharing (area-based FU, Table 3) and land-sharing (modified-area based FU, Table 3), respectively.

$$\eta = \left(\frac{M_A}{M_c} + \frac{S_A}{S_c}\right) \times \frac{1}{2} \quad (2)$$

Where M_A is crop yield under the agrivoltaic system, M_c is crop yield under the conventional system, S_A is the surface area not covered by OPV and S_c is the surface area under the conventional system. Substituting the values for the present agrivoltaic system in eqs. (1) and (2), we get the following result:

$$0.86 \times 24.9 + (1-0.86) \times 17.7 = 23.9 \quad (1')$$

$$\eta = \left(\frac{1513}{1669} + \frac{290}{356}\right) \times \frac{1}{2} = 0.86 \quad (2')$$

Where 24.9 and 17.7 were the LC-CO_2 emissions (in kg-eq CO_2) when sunlight-sharing and land-sharing were taken into account, respectively (Table 3) and 1669 and 1513 were the tomato yields (in kg) under the conventional and agrivoltaic systems, respectively, observed in the case experimental farm of the present study. Further, 290 (i.e., 356–66) and 356 were the areas (in m^2) not covered by OPV and the surface area under the conventional system, respectively. The LC-CO_2 emissions under the agrivoltaic system when both the functions were addressed were 23.9 (in kg-eq CO_2). This value will fall between the following two extremes: In case of a conventional tomato field, η is 1 ($\frac{M_A}{M_c}$ is 1 and $\frac{S_A}{S_c}$ is 1), the LC-CO_2 emissions is represented by LC-CO_2 (S), according to eq.

(1); whereas, in case of a field with only OPV, η is 0, ($\frac{M_A}{M_c}$ is 0 and $\frac{S_A}{S_c}$ is 0), and the LC-CO_2 emissions is represented by LC-CO_2(L).

5. Conclusions

An agrivoltaic system is one in which power generation by PV modules is combined with crop production on the same land. In this system, certain functions, namely sunlight sharing, land sharing, and power generation, are additional to the conventional functions of agricultural production systems. In order to address the functions unique to the agrivoltaic system, the present study proposed two new FUs: modified area-based and monetary-based. These new FUs aimed to help understand the environmental impacts better. Particularly, combinations of several FUs can help in maintaining focus on crop production as the main function of agricultural land. Finally, as the sunlight and land sharing happen simultaneously, the present study proposed a method to address them together while reporting of environmental impacts.

It has been slightly less than a decade since the first experiment on agrivoltaic systems was conducted (Dinesh and Pearce, 2016). Further research is required on the topic of influence of functional units on LCA results for a wide range of crops.

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