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The socio-economic impacts of introducing circular economy into Mediterranean rice production

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Research Highlight：

- The first hybrid life cycle assessment model for rice production system.
- Gross value added and employment of conventional and circular rice supply chain were evaluated.
- Gross value added and employment opportunity reallocated from fossil fuel based sector to bio-economy based sector.
- The total positive social-economic impacts of the circular rice system are not necessarily more than the conventional rice system.

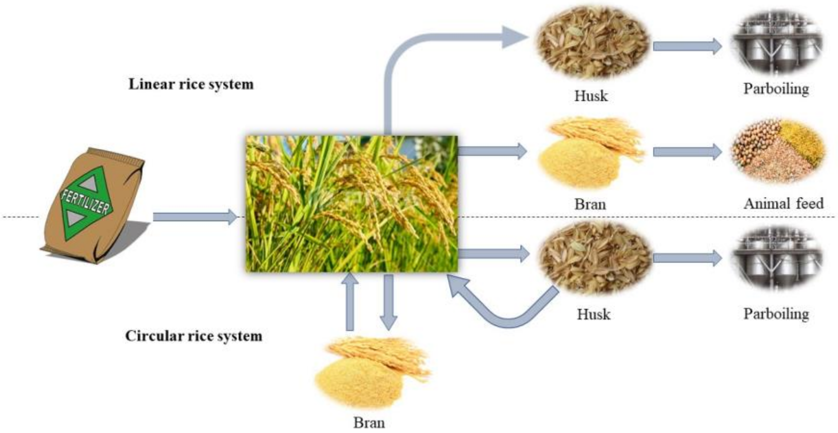
Abstract:

A novel bio-fertilizer technology was developed to utilize paddy rice residues (bran and husk) through composting. The bio-fertilizer can recycle the nutrients in residues to replaces synthetic fertilizer within the rice production system. To evaluate the feasibility and potential benefits of this circular rice production system, a hybrid life cycle assessment model was developed to estimate social-economic impact. The model combined the multi-regional input-output database, Exiobase, with engineering process data for conventional and circular rice production systems from the Agrocycle project.

The gross value added and employment in each system were compared at functional unit and sectoral level. The results indicated the efficiency of fertilizer application has a significant effect on social-economic impacts. The circular system has the potential to increase the gross value added and employment compared to conventional rice production, but the circular rice system could not improve both economic and social impacts at the same time. The results indicated the circular system did not necessarily achieve more positive social-economic impacts than the convention linear system. Considering the circularity and efficient use of resources, the bio-fertilizer technology should not be dismissed. To derive better social-economic performance from the circular rice supply chain, further developments are required, such as technology development to reduce unit production cost and infrastructure development to support bio-fertilizer production.

Key words: Rice, Circular economy, Hybrid life cycle assessment, Social-economic impacts

Graphical abstract



1. Introduction

Rice is an important global food crop, which not only makes a significant contribution to food security and agricultural economy, but also leads to many environmental impacts (Lobell et al., 2011). The top ten most important global rice producers are in Asia (China and India being the top two). Although Europe is only responsible for a small share of global rice production, it is an important ingredient in much Mediterranean cuisine, (Khush, 1997), and has cultural significance with long history (Son et al., 2014). Therefore, the rice production in Europe is important.

In past decades, rice research focused on nutrient management (Dobermann et al., 2002) and crop genetics (Matsumoto et al., 2005), reflecting the importance of the green revolution (Evenson and Gollin, 2003). However, the research emphasis has moved to the sustainability of rice production since the beginning of the 21st century, and life cycle assessment (LCA) (ISO, 2006a) began to be used to evaluate the environmental performance of rice supply chains (Blengini and Busto, 2009; Brodt et al., 2014). Recent LCA application for environmental research into rice systems mainly focused on three aspects: reduction of nutrient loss, comparison of production systems and utilization of by-product within the rice supply chain. Cai et al. (2018) reduced the synthetic fertilizer application in rice system by using legumes. Leon and Kohyama (2017) evaluated nitrogen and phosphorus losses from lowland paddy rice fields. The conventional and organic rice production systems were compared for different regions and climatic circumstances (He et al., 2018; Hokazono and Hayashi, 2012; Yodkhum et al., 2017). The by-product rice straw has potential to be feedstock for bio-energy production (Prasara-A and Gheewala, 2017), which could reduce environmental impact compared to waste valorisation for bio-fertilizer production (Silalertruksa and Gheewala, 2013). However, Rathnayake et al. (2018) also found bioethanol production from rice straw has less advantage than the residue of other crops, e.g. cassava, cane molasses. The other waste valorisation options for rice residues include bioplastics (Bilo et al., 2018), adsorbents (Sangon et al., 2018) and building materials (Qin et al., 2018).

Although research has covered a wide range of environmental topics, there is no LCA study that has investigated the effect of nutrient recycling within the rice production system, especially the broad social-economic impacts at sectoral level. In addition, most of published rice LCA studies have used conventional process-based LCA, which may suffer from the incomplete system boundary issue and fail to capture the total impacts from background sectors (Wiedmann et al., 2011). Pagotto and Halog (2015) attempted to use hybrid LCA to evaluate the sectoral effect of circular economy for the agri-food sector, but their method was not designed to assess the impacts of a specific circular economy technology (Genovese et al., 2017).

Nutrient recycling is one of many circular economy approaches, which is promoted as a sustainable business model with great market potential for the European agriculture and food sector (SYSTEMIQ, 2017). Rice bran and husk are the most important residues from paddy rice, accounting for 0.05-0.1 kg bran and 0.28 kg husk per 1 kg rice harvested (Rice Knowledge Bank, 2017). Currently, rice bran and husk are not used for recycling nutrient in conventional rice systems. The rice husk has no commercial value and is typically burned for heat with steam generated being used for parboiling the rice (Ahiduzzaman and Sadrul Islam, 2009). Rice bran is generally used as an ingredient for animal feed, and has a relatively low price despite having a high nutrient value (Sharif et al., 2014). Although a study has demonstrated the feasibility of using husk to produce bio-fertilizer by composting (Lim et al., 2012), there is no research that investigated the impacts of valorising paddy rice residues (rice bran and husk) within rice production system. The effect of technology or business model on social-economic performance can be product and region specific (Zhao et al., 2017). To better understand the effect of circular economy (nutrient valorisation) on a particular rice supply chain, a comprehensive social-economic impact evaluation is needed.

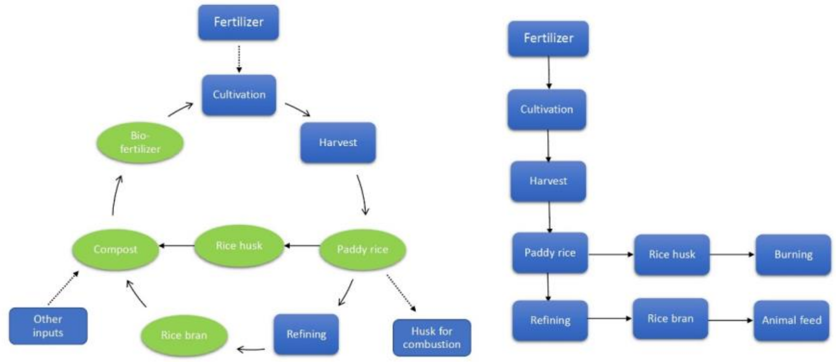
The objective of this study was conceived to understand the socio-economic implications of recovering nutrients (rice bran and husk) from residues to recirculate to the next crop as an example of circular bio-economy. This study used site-specific production data from a novel bio-fertilizer technology developed by the Hellenic Agricultural Organisation in Greece as part of the Horizon 2020 project '*AgroCycle*'. It was assumed that the bio-fertilizer produced would replace mineral fertilizer for Greek rice production, thus partly circularizing the nutrient requirement from one growing season to the next. To capture the comprehensive social-economic impact of this circular rice supply chain, an integrated evaluation approach was adopted (Venkata Mohan et al., 2016). A hybrid LCA model with full system boundary was developed

2. Methods

2.1 The rice production system

The supply chains for rice grown in Greece were defined (1) conventional 'linear' rice production, and (2) the *AgroCycle* ‘circular’ system with nutrient recovery by composting (outlined in Figure 1). For the conventional system, mineral fertilizer (NPK) was used during cultivation and was applied three times in one year (Table 1). Normal agronomic practices were adopted for husbandry and rice was harvested when the grain moisture ranged from 19-21% (Ntanos, 1997). The harvested rice was dehulled generating rice husk equivalent to 20% of the unprocessed paddy rice by mass (Rice Knowledge Bank, 2017). The rice husk was combusted to produce steam used for parboiling the rice. After subsequent milling bran residue was assumed to be 10% of the paddy rice, which was used as animal feed ingredient (Sharif et al., 2014). For the *AgroCycle* system, 100% of bran and 6.25% of husk were redirected as substrate for composting, with the remainder assumed to be used as normal (Ahiduzzaman and Sadrul Islam, 2009). The composting takes about one month and includes chicken litter, water, zeolite and a composting accelerator (NEUDORFF Radivit).

Figure.1 System diagram of circular and linear rice production systems



AgroCycle

Conventional

To compare the circular and linear rice systems, experiments with conventional fertilizer and bio-fertilizer application were carried (Table 1). The amount of bio-fertilizer application increased from AgroCycle 1 to AgroCycle 3. AgroCycle 2 provided the same level of nutrients as the conventional system. The experiment was set up as a randomized block trial with four fertilizer treatments. Based on unit farm land (ha), the paddy rice productivity of the four systems was compared. The outputs of conventional and AgroCycle systems are shown in Table 1. The inputs required to produce 1 tonne paddy rice by both systems were costed (Table 2). Due to the confidentiality of the bio-fertilizer composition, the exact amalgamation has not been disclosed and ‘x’ is used as a placeholder for digits in the actual numbers. The activity data for mineral fertilizer use, bio-fertilizer use (AgroCycle), irrigation, and yield were taken from field experiments conducted by the Hellenic Agricultural Organisation in Greece. Costs for zeolite, RADIVIT, irrigation, land rent and pesticide application were taken from local market prices recorded during the experiments in 2017. The costs of synthetic fertilizer were calculated based on the average NPK fertilizer cost in Greece

(Eurostat, 2016). The Greek water price was taken from Marinopoulos and Katsifarakis (2017). The on-farm diesel consumption was estimated based on fuel use by farm machinery for crop production (Pelletier et al., 2014). A transport distance of 30 km for mineral fertilizer and composting substrate was estimated from Blengini and Busto (2009). Based on fuel consumption, the cost of transport was estimated. The cost of fuel was assumed to be 20% of total transport cost (Karlaftis and McCarthy, 2002). The diesel consumption were taken from Ecoinvent (Wernet et al., 2016), and the price of diesel was from European Energy Portal (https://www.energy.eu/). The cost of labour and seed were derived from European commission (2008). The price of rice bran was estimated from FAO (1998), which was 35% of paddy rice price. Although there is no standard price for rice husk, it was estimated from its thermal energy content (Ahiduzzaman and Sadrul Islam, 2009) and the cost of replacing gas for thermal energy (Eurostat, 2017).

Table 1. The amount of nitrogen (kg) and paddy rice output (tonne) per ha land

Treatments	**Basic N units**	**1st surface N units at tillering**	**2nd surface N units at booting**	**Rice output**
AgroCycle 1	35	35	10	8
AgroCycle 2	70	70	20	8.9
AgroCycle 3	140	140	40	10.3
Conventional	70	70	20	7

Table 2. Inputs and costs for one tonne of paddy rice produced in both systems

Input	**AgroCycle 1**		**AgroCycle 2**		**AgroCycle 3**		**Conventional**	
	Quantity	**Value (€)**	**Quantity**	**Value (€)**	**Quantity**	**Value (€)**	**Quantity**	**Value (€)**
Rice bran fertilizer (kg)	XX.XX	N/A	XX.XX	N/A	XXX.XX	N/A	N/A	N/A
Zeolite (kg)	X.XX	28.07	X.XX	50.46	X.XX	87.20	N/A	N/A
RADIVIT (kg)	XXX.XX	4.14	XXX.XX	7.45	XXXX.XX	12.88	N/A	N/A
Water (L)	XX.XX	0.47	XXX.XX	0.85	XXX.XX	1.47	N/A	N/A
Chicken manure (kg)	XXX.XX	N/A	XXX.XX	N/A	XXX.XX	N/A	N/A	N/A
Rice bran (kg)	XX.XX	24.55	XX.XX	44.13	XXX.XX	76.26	N/A	N/A
Rice husk (kg)	XX.XX	4.22	XX.XX	7.59	XXX.XX	13.12	N/A	N/A
Irrigation water (L)	**1500**	17.91	**1348.31**	**16.10**	**1165.05**	**13.91**	**1714.29**	**20.47**
Diesel (farming machine activities) (L)	**7.60**	8.56	6.99	**7.87**	6.18	**6.96**	**7.2**	8.11
Seeds (kg)	**25.00**	15.73	22.47	**14.14**	19.42	**12.22**	**28.57**	17.98
Compound fertilizer NPK (32:5:5) (kg)	N/A	N/A	N/A	N/A	N/A	N/A	**71.24**	N/A
Nitrogen (Urea) (kg)	N/A	N/A	N/A	N/A	N/A	N/A	49.56	21.81
Phosphorus (P2O5) (kg)	N/A	N/A	N/A	N/A	N/A	N/A	8.16	2.92
Potassium (K2O) (kg)	N/A	N/A	N/A	N/A	N/A	N/A	4.29	2.81
Pesticide (kg)	N/A	N/A	N/A	N/A	N/A	N/A	**0.88**	**22.63**
Rent (ha)	**0.125**	**87.50**	**0.112**	80.49	**0.097**	69.55	**0.14**	**102.34**
Transportation (tkm)	**8.17**	2.61	**14.68**	4.69	**25.37**	8.10	**7.31**	**2.33**

2.2 Definition of scenarios

To understand the impacts of paddy rice production with conventional and (AgroCycle) circular technologies, evaluation was carried out at both unit product level and sectoral level. At product level, the functional unit was one tonne of paddy rice and no market scenario was considered. At sectoral level, the maximum impact of AgroCycle technology on the wider economy was investigated, which was determined by the market share of *AgroCycle* technology and restricted by the availability of rice bran from the Greek rice sector.

For sectoral evaluation, farm land was the main limit to adopting AgroCycle technology and it was assumed the total land for rice farming remained constant. According to the availability of rice bran (10% of paddy rice) and demand for rice bran in bio-fertilizer production, the maximum proportion of land (P_b) converting from synthetic fertilizer to bio-fertilizer can be estimated in equation 1 and 2. In addition, considering the fertilizer use efficiency (Table 1), the technology from AgroCycle 1 (the most efficient technology) was chosen as the replacement bio-fertilizer. The land for synthetic fertilizer (L_{sn}) and bio-fertilizer (L_{bn}) used in year n (n≥2) was calculate as:

$$L_{bn} = [(7000 \times L_{s(n-1)} + 8000 \times L_{b(n-1)}) \times 10\%]/2426 \quad (1)$$

$$P_b = L_{bn} / (L_{sn} + L_{bn}) \quad (2)$$

where 7000 (kg/ha) and 8000 (kg/ha) are rice productivity for conventional and AgroCycle rice production technology, and 2426 is the demand (kg) of rice bran in bio-fertilizer for one ha land. P_b is the proportion of rice farming land with AgroCycle technology and this ratio would be in equilibrium in the 4th year with a maximum value close to 28%. According to this proportion, we defined 28 scenarios to depict the Greek rice sector by potential market share of AgroCycle technology in Table 3.

Table 3. Share of Greek paddy rice production with both technologies

	Baseline	**Scenario 1**	···	**Scenario 27**	**Scenario 28**
Conventional	99%	98%	···	73%	72%
AgroCycle	1%	2%	···	27%	28%

2.3 Hybrid LCA methodology

Input-output (IO) analysis uses a top-down, economic method to capture product and service flows from one industrial sector to all other sectors within one country, region or multi-regions (Miller and Blair, 2009). The IO table is a technical coefficient matrix representing the input and output configurations of each industrial sector within a certain period of time. The methodological theory was described by the Leontief model (Leontief, 1951), where A is the technical coefficient matrix, f is the final demand matrix and X is total output.

$$X = (1\text{-}A)^{-1}f \qquad (3)$$

Hybrid LCA is a powerful technique that combines national economic IO data with process level data (Suh, 2004). It can capture the social-economic impacts of interconnected supply chains (Crawford et al., 2018). Hybrid LCA can both eliminate the effect of an incomplete system boundary in process-based LCA by including sectoral relationships, but also maintains the detailed engineering information of specific processes within the studied system (Suh and Huppes, 2005). To capture the specific detail of nutrient circulation technology and the conventional linear system, the implementation of hybrid LCA model followed the approach of Koelbl et al. (2016).

Gross added value (GVA) and employment were used as the social-economic indicators.

Based on the system described, the hybrid LCA model was created in MATLAB by integrating the bottom-up engineering process information of rice production systems with the top-down, multi-regional input-output database EXIOBASE, which contains 9800 sectors from 49 regions (200 sectors each) around the world (Wood et al., 2014). To develop the hybrid social LCA model, a number of steps were followed. First the hybrid technical coefficient matrix A_{hybrid} was constructed with new sectors for AgroCycle and conventional paddy rice production in Greece.

$$\mathrm{A}_{hybrid} = \begin{bmatrix} \mathrm{A}_{r,r} & \mathrm{A}_{r,p} \\ \mathrm{A}_{p,r} & \mathrm{A}_{exio} \end{bmatrix} \tag{4}$$

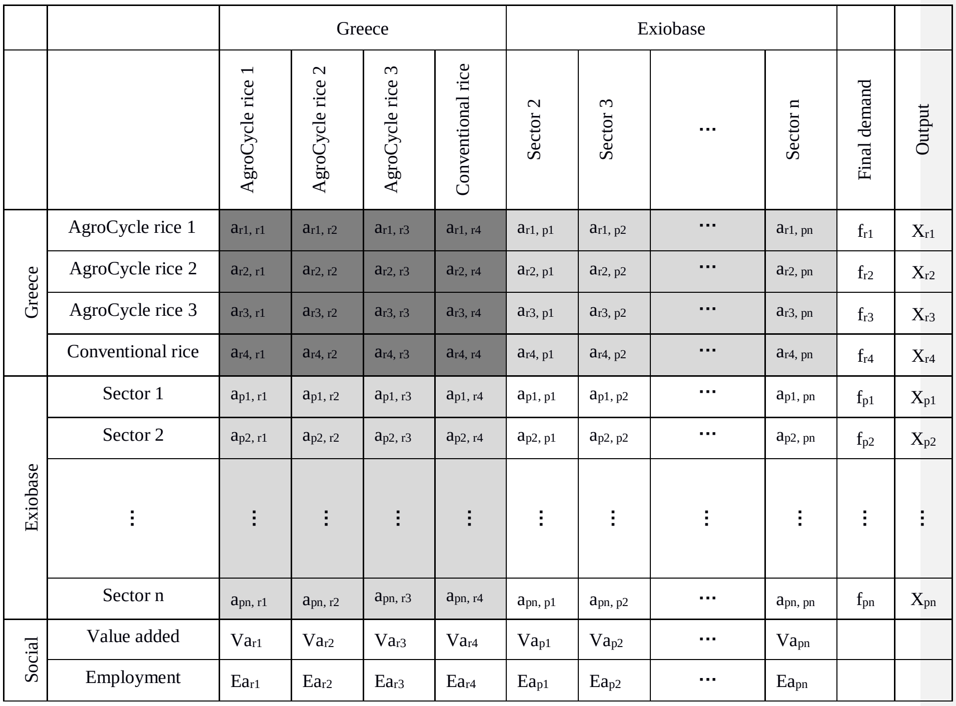
The A_{hybrid} matrix contained 4 sub-matrixes for intermediate technology coefficients, where $\mathrm{A}_{r,r}$ are the input coefficients within the rice sectors, $\mathrm{A}_{r,p}$ are the coefficients for rice to other sectors, and $\mathrm{A}_{p,r}$ are the coefficients from other sectors to the rice sectors. A_{exio} is the original product-by-product IO matrix in Exiobase version 3.

$$\mathrm{A}_{r,r} = \begin{bmatrix} \mathrm{a}_{\mathrm{r1,r1}} & \cdots & \mathrm{a}_{\mathrm{r1,r4}} \\ \vdots & \ddots & \vdots \\ \mathrm{a}_{\mathrm{r4,r1}} & \cdots & \mathrm{a}_{\mathrm{r4,r4}} \end{bmatrix},\ \mathrm{A}_{r,p} = \begin{bmatrix} \mathrm{a}_{\mathrm{r1,p1}} & \mathrm{a}_{\mathrm{r1,p2}} \cdots \mathrm{a}_{\mathrm{r1,pn}} \\ \mathrm{a}_{\mathrm{r2,p1}} & \mathrm{a}_{\mathrm{r2,p2}} \cdots \mathrm{a}_{\mathrm{r2,pn}} \end{bmatrix}, \tag{5}$$

$$\mathrm{A}_{p,r} = \begin{bmatrix} \mathrm{a}_{\mathrm{p1,r1}} & \mathrm{a}_{\mathrm{p1,r2}} \\ \mathrm{a}_{\mathrm{p2,r1}} & \mathrm{a}_{\mathrm{p2,r2}} \\ \vdots & \vdots \\ \mathrm{a}_{\mathrm{pn,r1}} & \mathrm{a}_{\mathrm{pn,r2}} \end{bmatrix},\ \mathrm{A}_{exio} = \begin{bmatrix} \mathrm{a}_{\mathrm{p1,p1}} & \cdots & \mathrm{a}_{\mathrm{pn,p1}} \\ \vdots & \ddots & \vdots \\ \mathrm{a}_{\mathrm{p2,pn}} & \cdots & \mathrm{a}_{\mathrm{pn,pn}} \end{bmatrix},$$

Where $\mathrm{A}_{r,r}$ is a four by four diagonal matrix containing the intermediate input coefficients within rice sectors, $\mathrm{A}_{p,r}$ has 9800 rows and 4 columns, reflecting the input flows of upstream sectors to the foreground system, $\mathrm{A}_{r,p}$ has 4 rows and 9800 columns with distribution information about the product or service from the foreground system to background IO systems (Figure 2). Due to the minor contribution of the downstream sector on the overall results (Suh, 2006), it was assumed $A_{r,p}$ had the same downstream distribution in the Greek paddy rice sector as n originally in Exiobase (Wiedmann et al., 2011).

Figure. 2 Modification of Exiobase



		Greece				Exiobase					
		AgroCycle rice 1	AgroCycle rice 2	AgroCycle rice 3	Conventional rice	Sector 2	Sector 3	⋯	Sector n	Final demand	Output
Greece	AgroCycle rice 1	$a_{r1, r1}$	$a_{r1, r2}$	$a_{r1, r3}$	$a_{r1, r4}$	$a_{r1, p1}$	$a_{r1, p2}$	⋯	$a_{r1, pn}$	f_{r1}	X_{r1}
	AgroCycle rice 2	$a_{r2, r1}$	$a_{r2, r2}$	$a_{r2, r3}$	$a_{r2, r4}$	$a_{r2, p1}$	$a_{r2, p2}$	⋯	$a_{r2, pn}$	f_{r2}	X_{r2}
	AgroCycle rice 3	$a_{r3, r1}$	$a_{r3, r2}$	$a_{r3, r3}$	$a_{r3, r4}$	$a_{r3, p1}$	$a_{r3, p2}$	⋯	$a_{r3, pn}$	f_{r3}	X_{r3}
	Conventional rice	$a_{r4, r1}$	$a_{r4, r2}$	$a_{r4, r3}$	$a_{r4, r4}$	$a_{r4, p1}$	$a_{r4, p2}$	⋯	$a_{r4, pn}$	f_{r4}	X_{r4}
Exiobase	Sector 1	$a_{p1, r1}$	$a_{p1, r2}$	$a_{p1, r3}$	$a_{p1, r4}$	$a_{p1, p1}$	$a_{p1, p2}$	⋯	$a_{p1, pn}$	f_{p1}	X_{p1}
	Sector 2	$a_{p2, r1}$	$a_{p2, r2}$	$a_{p2, r3}$	$a_{p2, r4}$	$a_{p2, p1}$	$a_{p2, p2}$	⋯	$a_{p2, pn}$	f_{p2}	X_{p2}
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Sector n	$a_{pn, r1}$	$a_{pn, r2}$	$a_{pn, r3}$	$a_{pn, r4}$	$a_{pn, p1}$	$a_{pn, p2}$	⋯	$a_{pn, pn}$	f_{pn}	X_{pn}
Social	Value added	Va_{r1}	Va_{r2}	Va_{r3}	Va_{r4}	Va_{p1}	Va_{p2}	⋯	Va_{pn}		
	Employment	Ea_{r1}	Ea_{r2}	Ea_{r3}	Ea_{r4}	Ea_{p1}	Ea_{p2}	⋯	Ea_{pn}		

To construct $A_{p,r}$, a concordance (Table 3) was constructed to map the cost flows of the rice systems to relevant sectors in the IO table. The corresponding sectors for each region in Exiobase were aggregated into the same cost structure as the cost flows for the rice systems. All the import shares were in the same proportion as in Exiobase. Then, the aggregated coefficients for Greek paddy rice in Exiobase were divided by the cost structures of rice systems to get a scalar multiplier. This scalar multiplier was multiplied by the concordance and the column for the Greek paddy rice sector in the original Exiobase to establish $A_{p,r}$. Therefore, the production costs of rice were disaggregated according to the proportions of A matrix in Exiobase. The inputs already captured in $A_{r,r}$ would be deleted and the subsidy was treated as part of the value-added account.

Table 3. Distribution of cost in EXIOBASE

Cost categories	AgroCycle	Conventional
Fertilizer cost	Distribute “Zeolite” to “Chemical and fertilizer minerals, salt and other mining and quarrying products nec”, and “RADIVIT” to “Chemicals nec.”, “Rice bran” to “Food product nec.”, “Rice husk” to “Electricity by biomass and waste”, “water” to "Collected and purified water, distribution services of water"	Distribute to "N-fertiliser" and "P and other fertiliser”.
Irrigation cost	Distribute “Irrigation” to "Collected and purified water, distribution services of water".	
Fuel cost	Distribute “diesel cost” to "Gas/Diesel Oil".	
Crop protection	n.a	Distribute “pesticide” to "Chemicals nec",
Seed cost	Distribute “Rice seed cost” to "Paddy rice".	
Transport cost	Distribute “truck transport” to "Other land transportation services ".	
Rent cost	Distribute “land rent service” to " Real estate services".	

For sectoral evaluation, A_{hybrid} was be modified. The main changes were made in $A_{r,r}$ and $A_{r,p}$, and because only AgroCycle 1 and conventional technology were chosen for scenarios analysis, the dimension of $A_{r,r}$ were a two by two matrix. To investigate the change of sectoral social-economic impacts in each scenario, the market share of AgroCycle technology was used to re-distribute the elements in $\mathrm{A}_{r,r}$ and $\mathrm{A}_{r,p}$. The coefficients within rice sectors and IO system were replaced in following steps. First, according to the physical share of two rice systems in market (Table 3), the economic share $(S_{ri,S})$ was calculated for rice by two production technologies.

$$S_{ri,S} = \frac{C_{ri} \times P_{ri,s}}{\sum C_{ri} \times P_{ri,s}} \tag{6}$$

where, C_{ri} is the production cost of rice with technology *i* (conventional or *AgroCycle*), $P_{ri,s}$ is physical share of rice from technology *i* in scenario *s*. The input coefficients for each column of $\mathrm{A}_{r,r}$ *and* $\mathrm{A}_{r,p}$ were then replaced based on the economic share of the two types of rice in the market $(S_{ri,S})$ as:

$$\mathrm{a}_{\mathrm{ri,rj,s}} = (\mathrm{a}_{\mathrm{r1,rj}} + \mathrm{a}_{\mathrm{r2,rj}}) \times S_{ri,S} \tag{7}$$

$$\mathrm{a}_{\mathrm{ri,pn,s}} = (\mathrm{a}_{\mathrm{r1,pn}} + \mathrm{a}_{\mathrm{r2,pn}}) \times S_{ri,S} \tag{8}$$

Therefore, the modified $\mathrm{A}_{\mathrm{h}ybrid}$ matrix with scenario *s* became $\mathrm{A}_{\mathrm{h}ybrid-s}$:

$$\mathrm{A}_{\mathrm{h}ybrid-s} = \begin{bmatrix} \mathrm{A}_{r,r,s} & \mathrm{A}_{r,p,s} \\ \mathrm{A}_{p,r} & \mathrm{A}_{exio} \end{bmatrix} \tag{9}$$

According to the Leontief model, the total output for the hybrid technology coefficients matrix can be calculated as:

$$\begin{bmatrix} \mathrm{X}_{r} \\ \mathrm{X}_{IO} \end{bmatrix} = (\mathrm{I}-\mathrm{A}_{hybrid})^{-1} * \begin{bmatrix} \mathrm{f}_{r} \\ \mathrm{f}_{IO} \end{bmatrix} = \mathrm{L}_{hybrid} * \begin{bmatrix} \mathrm{f}_{r} \\ \mathrm{f}_{IO} \end{bmatrix} \tag{10}$$

To investigate the social-economic impacts of unit rice production with different technologies and their potential impacts at sectoral level, the final demand (f_{r}) as a unit product comparison was defined as one tonne of paddy rice. For the sectoral evaluation, total land for rice farming was assumed to remain constant. The final demand was calculated based on sectoral paddy rice production from Greek central

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statistics office data (S. Spyroulis, 2017) and the sectoral share of the two rice system was defined by the above scenarios. The final demand for AgroCycle rice and conventional rice was redistributed in the same ratio of the market share in the scenarios. The demand of other sectors was defined as ‘0’. Therefore, the social-economic impacts were calculated as:

$$B*\begin{bmatrix} X_r \\ 0 \end{bmatrix} = B*L_{hybrid}*\begin{bmatrix} f_r \\ 0 \end{bmatrix} \qquad (11)$$

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where B is the row vector and represents GVA and employment intensity per unit of output (x). The foreground GVA and employment intensity were estimated from Greek central statistics office data (S. Spyroulis, 2017) and the Ricepedia website (http://www.ricepedia.org/greece), and the background information was taken from Exiobase.

3. Results and discussion

3.1 Impacts of unit paddy rice production

Based on one functional unit (one tonne) of paddy rice production, the conventional (Co) and AgroCycle 1 (A1) technology made a similar contribution to total GVA (Table 4). The total GVA decreased from A1 (258 euro/tonne) to A3 (180 euro/tonne), an almost 30% reduction. For employment, conventional rice supply chain supported more job creation than the AgroCycle systems, but the employment rate increased from A1 to A3. However, even in A3, the employment rate was still 9% lower than Co.

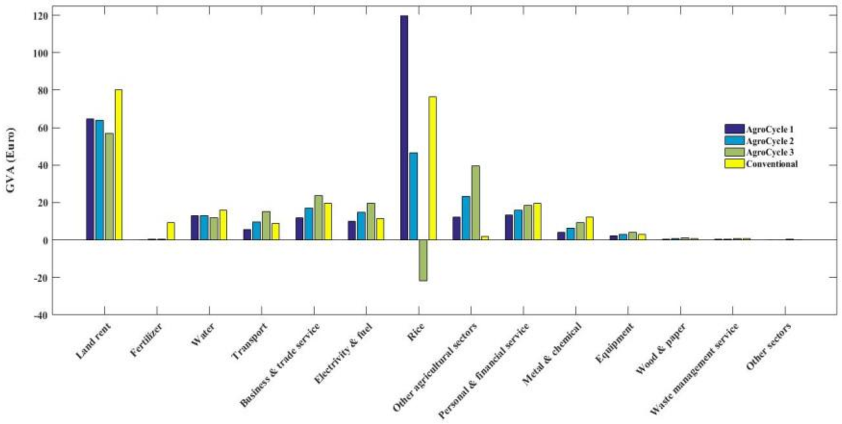
Table 4. Impacts of 1 tonne paddy rice production with AgroCycle and conventional technologies

	AgroCycle 1	**AgroCycle 2**	**AgroCycle 3**	**Conventional**
Total GVA (euro/tonne)	257.55	215.63	180.19	259.88
Total EMP (person/ tonne)	1.77E-02	1.78E-02	1.87E-02	2.06E-02

When the impacts of all sectors were aggregated into 14 main sector categories (Figure 3), the contribution to GVA from paddy rice and land rent accounted for around 50% to 72% of total GVA in all systems, except for A3. It was noted that GVA of both sectors decreased from A1 to A3. However, for the land rent sector, the productivity per unit land was improved, which increased the land use efficiency and lowered the land cost in unit paddy rice production. For the paddy rice sector, comparing GVA in Co and A1 showed an improvement of 56%. This implied reducing nutrients input (Table 1) and applying more efficient fertilizer application would significantly improve the GVA of Greek paddy rice sector. The fertilizer application in Co reflected the average fertilizer use in the Greek rice sector, which is very inefficient (Eleftherohorinos et al., 2002), and a lack of regulation. The excessive bio-fertilizer application in A2 and A3 could lead to high production cost and reduced the profitability. The GVA of rice sector in A3 had a negative value. In general, the GVA in other sectors increased from A1 to A3. Fertilizer and the ‘other agricultural’ sector had the most significant changes of GVA among the other sectors. The change of GVA in the fertilizer sector was due to the shift of synthetic fertilizer to bio-fertilizer. For ‘other agricultural’ sector, the rice bran taken from the animal feed sector would increase the demand of other agricultural products as feed ingredients. Overall, in terms of the same nutrient input, the bio-fertilizer technology from AgroCycle may decrease the total GVA (A2 and Co). However, optimizing the bio-fertilizer application (A1) could maintain the total GVA driven by the current Greek paddy rice sector. The efficiency of bio-fertilizer application would determine reallocation of GVA between different sectors, especially for the paddy rice sector. This conformed with previous findings that the main impacts of the circular food supply chain are in foreground systems (Genovese et al., 2017).

Similar to GVA, the main contribution of employment was from the paddy rice sector. It accounted for around 50% to 70% of total employment in all systems. In contrast to total employment, the labour requirement in the paddy rice and land rent sector decreased from A1 to A3. The increasing productivity per unit land was the main reason for the reduction of employment in both sectors. The decreased labour requirement indicated the bio-fertilizer systems were more labour efficient. It was a positive impact for the paddy rice production. The employment in other sector categories increased from A1 to A3. The most notable improvement was in the ‘other agricultural’ sectors. The demand of other agricultural products for feed ingredients was the main factor creating more jobs in this sector and total employment in wider economy. The total employment excluding rice and land rent sector (Table 5) showed that based on the employment of the conventional system, the change of total employment in A2 and A3 increased by 9% and 58%, respectively. This demonstrated the AgroCycle system has the potential to create more employment opportunity in background sectors. For the most efficient system (A1), the employment in background sectors decreased by 20%. This implies that promotion of efficient AgroCycle system needs further consideration of the employment performance of this circular rice supply chain, and it is necessary to develop the relevant supporting sectors for circular rice production (e.g. more research activities) and to scale-up bio-fertilizer production. The development example can be improvement of bio-fertilizer technology, which requires more research activities. Developing better circular supply chain needs more business services such as banking, insurance, accounting and property. Scaling up bio-fertilizer production will demand more facilities and hardware, such as manufacture equipment, IT infrastructure and control systems to maintain services. All these developments would further contribute to employment associated with circular rice supply chain.

Figure. 3 GVA and employment per tonne of paddy rice production with AgroCycle and conventional technology



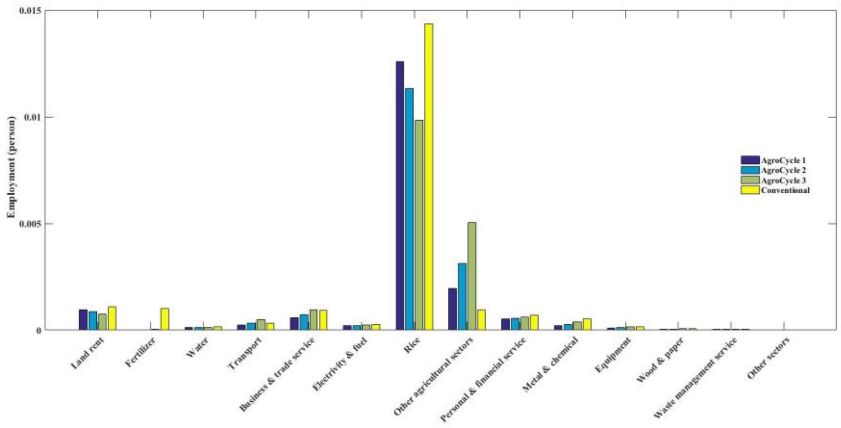


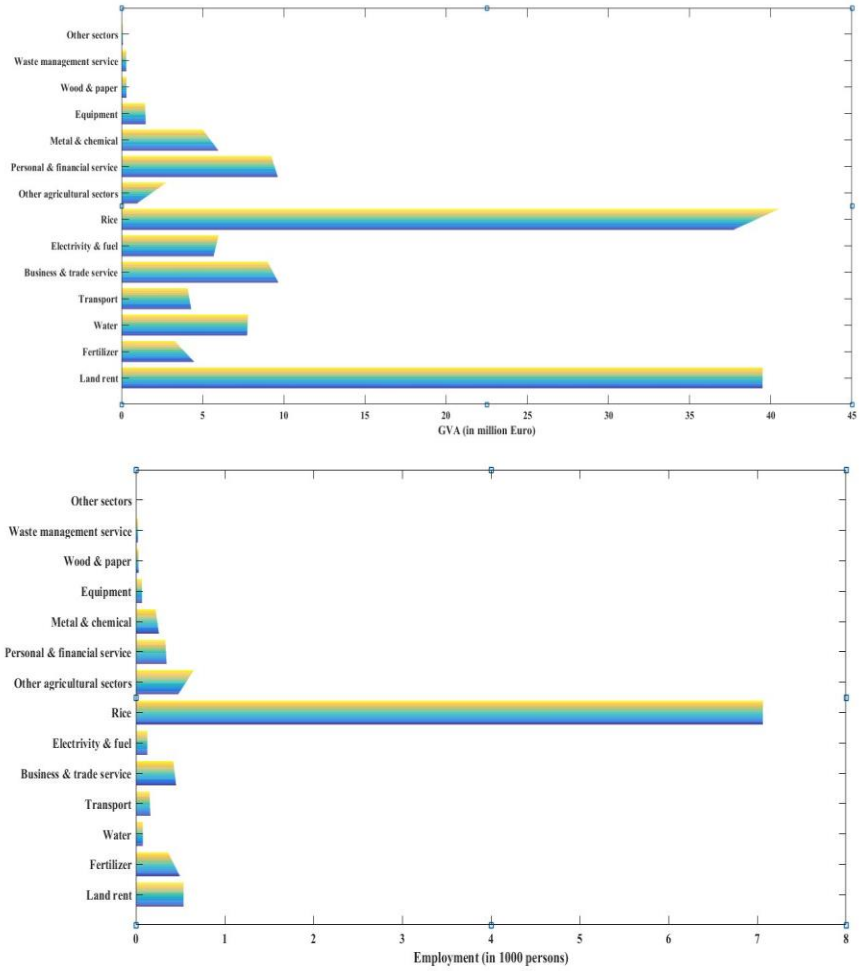
Table 5. Total employment excluding rice and land rent sectors

	AgroCycle 1	**AgroCycle 2**	**AgroCycle 3**	**Conventional**
Total EMP (person/ tonne)	4.11E-03 (-20%)	5.62E-03 (9%)	8.16E-03 (58%)	5.17E-03

3.2 Sectoral social-economic impact

The sectoral social-economic impacts of different market penetration with *AgroCycle* system were evaluated (Figure 4) in terms of change of sectoral GVA and employment contribution with different proportions of Co and A1 paddy rice supply systems. From blue to yellow, the bars stand for baseline scenario to scenario 28. Since the total land for rice farming was assumed to remain unchanged, the GVA from land rent was almost unchanged. The most significant increase of GVA was from the paddy rice sector. This was due to the better unit profitability of AgroCycle system and its higher yield per unit land. The shift from synthetic fertilizer to bio-fertilizer led to an increase in GVA in 'other agricultural' sectors and decreased GVA in the fertilizer, metal and chemical sectors. The GVA in personal and financial service, business and trade service, and transport sectors also decreased. This suggested the background supporting sectors for bio-fertilizer production created less GVA and further development will be required for improvement. The employment in most sectors did not change significantly. The employment in the paddy rice and land rent sectors was calculated based on total land for rice farming. Due to the shift of input demand, the most notable change of employment was from fertilizer and ‘other agricultural’ sectors.

Figure. 4 Change of GVA and employment of paddy rice production with different market share of AgroCycle technology



The contribution of GVA and employment in the scenario with maximum market penetration of AgroCycle technology was compared to the no AgrocCycle scenario (Table 6). When AgroCycle reached its maximum share in the Greek rice market, the total GVA was €128.28 million and total employment was 10080 person-jobs. Without

AgroCycle, there would be €1.44 million reduction in GVA (-1.13%) and 60 more person-jobs (0.59%). The changes of total social-economic impacts were quite small. The significant changes of social-economic impacts were in fertilizer, metal and chemical, and ‘other agricultural’ sectors. Although the change of GVA in the paddy rice sector was relatively small, its high share of total GVA indicated a considerable impact. Because the rice and land rent sector in Greece account for more than 60% of GVA and 70% of employment of new Greek rice supply chain. The main social-economic impacts are located within Greece. Less than 3% of GVA and employment was created outside of Greece, in UK, Hungary, Italy and Germany.

Table 6. The GVA and employment with maximum market share of AgroCycle technology

	GVA [a] (%)	**Change (%)**	**Employment [b] (%)**	**Change (%)**
Land rent	39.50 (30.6%)	0.0 (0.0%)	0.54 (5.3%)	0.00 (0.0%)
Fertilizer	3.29 (2.5%)	-1.2 (-26.5%)	0.36 (4.9%)	-0.13 (-26.8%)
Water	7.80 (6.0%)	0.1 (0.7%)	0.08 (0.8%)	0.00 (0.0%)
Transport	4.08 (3.2%)	-0.2 (-5.0%)	0.15 (1.6%)	-0.01 (-5.6%)
Business and trade service	9.01 (7.0%)	-0.7 (-6.8%)	0.42 (4.5%)	- 0.03 (7.0%)
Electricity and fuel	5.98 (4.6%)	0.3 (5.4%)	0.13 (1.3%)	0.00 (-1.8%)
Rice	40.48 (31.3%)	2.7 (7.3%)	7.07 (70.1%)	0.00 (0.0%)
Other agricultural	2.76 (2.1%)	1.8 (181.2%)	0.65 (4.8%)	0.17 (35.6%)
Personal and financial service	9.23 (7.1%)	-0.4 (-4.1%)	0.33 (3.4%)	-0.01 (-4.1%)
Metal and chemical	5.02 (3.9%)	-0.9 (-15.7%)	0.22 (2.6%)	-0.04 (-14.7%)
Equipment	1.45 (1.1%)	0.0 (0.0%)	0.07 (0.7%)	-0.00 (-3.7%)
Wood & paper	0.31 (0.2%)	0.0 (0.0%)	0.03 (0.3%)	-0.00 (-5.4%)
Waste service	0.30 (0.2%)	0.0 (0.0%)	0.02 (0.2%)	-0.00 (-1.3%)
Other sectors	0.08 (0.1%)	0.0 (0.0%)	0.01 (0.1%)	-0.00 (-3.8%)
Total	129.28 (100%)	1.44 (1.13%)	10.8 (100%)	-0.06 (-0.59%)

a: unit of GVA is million euro.   b: unit of employment is 1000 persons

3.3 Implications

Based on the results per unit paddy rice production, it can be concluded that the AgroCycle system (A2) created less GVA than the conventional system. This is similar to previous findings that pure economic performance of the circular model could be poorer than the linear model, because of characteristics of inputs material and energy (e.g. the source of energy) (Nasir et al., 2017) and the circular economy technology and model applied (Fan et al., 2018). However, choosing the more efficient AgroCycle option (A1) could retain a similar GVA per unit paddy rice production as the conventional system. At the sectoral level, due to the increased yield per unit land, the total sectoral economic performance would be improved. For employment, AgroCycle has better employment impact than the conventional system (A2 vs Co) at the unit product level. However, increasing the efficiency of the AgrocCycle system has a negative effect on employment. The sectoral level employment in the most efficient AgroCycle system (A1) and the conventional system was almost the same. Therefore, stakeholders of the rice sector need to make a trade-off decision between social and economic impacts when they adopt the current AgroCycle technology. This study draws attention to circular economy practices and the need for business models that consider the comprehensive social-economic impact of specific circular technology (nutrient recycling) on the whole economy, which is hardly even been investigated (Leipold and Petit-Boix, 2018). The results indicated that recycling the nutrients from paddy rice residue with current AgroCycle technology cannot improve all the social-economic impacts of the conventional rice system at the same time. The findings implied circular economy system does not necessarily improve the overall sustainability of a linear system (Lonca et al., 2018). However, some of resource in agriculture system is becoming increasing limited, e.g. farm land (Chakravorty et al., 2009),so a bio-fertilizer technology from AgroCycle could improve land use efficiency for rice production and reduce some land associated social-environmental issues (Tilman et al., 2009). An efficient bio-fertilizer application (A1) will increase the gross output from the rice sector with the same land resource. In addition, AgroCycle system is less dependent on fossil fuel and non-renewable mineral resources. Considering the limited supply of some natural elements (e.g. phosphorous) and ever increasing price of non-renewable resources (SYSTEMIQ, 2017), the AgroCycle system perhaps bears less risk of increasing production costs (e.g. variable price of synthetic fertilizer) and may have more economic advantage in the future. It is not reasonable to dismiss the bio-fertilizer route as the increase of circularity within the rice supply chain has much potential to lead positive impacts in the future.

In order to improve the overall social-economic impacts of the Agrocycle rice system, further technical and sectoral development is still required. For GVA, the main challenge of current AgroCycle technology is to reduce production cost and improve nutrients use efficiency per unit bio-fertilizer production. It demands further research both on fertilizer application and production process. For employment, since the main contribution was from rice farming, which was associated with total hectares of farming land. Adoption of conventional or AgroCycle technology would have no significant impact to the employment within rice sector. However, to exploit the full social benefit of a circular rice supply chain, the development of supporting sectors (e.g. research and education, business and trade, transport, and personal and financial service) also needs to happen.

Although hybrid LCA was not new, this study was the first attempt to apply hybrid LCA to bio-circular economy (rice production) with a focus of social-economic impacts, which was hardly been investigated in previous hybrid LCA. It shows the theoretical value of this approach for better understanding of the implications of adopting new technology in the agri-food domain. The results not only showed the impacts of the rice farming sector, but also revealed the extended interaction of rice production with the wider economy, which has not been evaluated in conventional rice LCA studies. These extended impacts have an important influence on the sustainability performance in the wider economy context and lead to significant political implication (Whetten, 1989) for development (e.g. technical direction, financial support) of circular economy in the agri-food sector.

3.4 Limitation and future research

In this study, the rebound effect (Vivanco and van der Voet, 2014) was not included. Based on the availability of rice bran and the input demands of AgroCycle technology, the maximum replaceable conventional rice system is 28%. Therefore, the sectoral increase of paddy rice is limited (Table 6). The higher productivity of the AgroCycle system was assumed unlikely to reduce paddy rice price and change consumption patterns in this study. However, this effect could be investigated in a future study. In addition, the environmental performance of circular rice systems also needs to be evaluated in future work to achieve a comprehensive evaluation of nutrient recycling model in rice sector

3. Conclusion

This study used hybrid LCA to evaluate the social-economic impacts of moving to a circular (nutrient recycling) from a conventional rice production system. Although the circular system showed potential to improve either gross value added or employment compared to the conventional rice system and reduced the risk of supply chain failure, the improvement cannot be achieved at the same time. The results indicated the positive impact of circular economy systems may not be less than conventional systems. To improve the AgroCycle technology in the rice sector, technology improvement and sectoral development in supporting sectors need to be achieved.

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