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Organic Vegetable Cultivation Reduces Resource and Environmental Costs While Increasing Farmers' Income in the North China Plain

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Abstract: Organic cultivation has been promoted in recent years as a possible alternative to conventional cultivation in order to reduce environmental burdens and nonrenewable resource use. However, a comprehensive assessment of the sustainability of different vegetable cultivation modes is currently lacking. In this study, a combined use of economic analysis (ECA), emergy analysis (EMA), and lifecycle assessment (LCA) was conducted to evaluate the economic performance, resource use, and environmental impacts of three greenhouse eggplant production modes, namely conventional (CON), low-input (LOW), and organic (ORG) cultivation. ECA results showed that the economic profit and value to cost ratio of ORG increased by 14%–17% and 36%–41% compared with CON and LOW, respectively. EMA results showed that ORG had higher resource use efficiency. The unit emergy value and emergy sustainability index of ORG increased by 37%–49% and 45%–65% than those of CON and LOW, respectively. LCA results revealed lower potential environmental impacts for ORG, and its total potential environment impact index was 80%–91% lower than that of CON and LOW. These results showed that organic vegetable cultivation reduced resource and environmental costs while increasing farmers' income, which is the most sustainable vegetable production mode in the North China Plain.

Keywords: greenhouse vegetable; organic cultivation; production efficiency; life cycle assessment; farming sustainability

1. Introduction

Vegetables are an indispensable food in people's daily lives and are very important to human health because they are a source of nutritional and nonnutritive food ingredients [1]. In the past two decades, the vegetable production in China has grown very rapidly, with the country's vegetable planting area reaching 22 million ha in 2015, accounting for 13% of the total crop area [2]. Among them, the greenhouse vegetable has been developed rapidly because it can get rid of the shackles of natural environment and traditional production conditions, and achieve high-yield and high-efficiency production mode. China is the world's largest country of greenhouse vegetable cultivation and has grown at a rate of about 10% per year in recent years. In 2017, the planting area of greenhouse vegetable reached approximately 3.5 million ha, and the output value of vegetables exceeded 700 billion RMB [3]. The rapid development of greenhouse vegetable industry has greatly promoted the employment of Chinese farmers and played a positive role in increasing their income. However, this off-season

production mode requires a lot of extra resources and energy, and the special closed environment and planting methods result in environmental issues that cannot be ignored. It was reported that vegetable cultivation has higher environmental risks than field crops, contributing to global warming, environmental acidification, and water eutrophication, mainly due to the low nutrient and water use efficiencies associated with the shallow root system for most vegetable species. [4]. According to a recent meta-analysis [5], the average annual input of fertilizer N in vegetable cultivation was about seven-times as much as the field crops. The average N_2O emission and nitrate leaching of greenhouse vegetable production system in China were 3.91 kg N_2O -N ha⁻¹ and 79.1 kg N ha⁻¹, significantly higher than those of field crops system.

At present, there are many studies on greenhouse vegetable production systems, mainly focusing on the agronomy and economic benefits of the cultivation modes [6] and microbial diversity [7]. Some researchers have also studied the environmental impact of greenhouse vegetable production, but have mainly focused on a certain aspect, such as greenhouse gas emissions [8] or pollution of reactive nitrogen [9]. However, since greenhouse vegetable production is no longer a mere vegetable-growing activity, it is aimed at vegetable production, including a "cradle-to-grave" production system of agricultural-materials production, agricultural cultivation, transportation, consumption and waste emissions. Traditional environmental impact assessment methods are often one-sided when evaluating agricultural production. Only from the perspective of the entire production system can the environmental impact of greenhouse vegetables be fully understood. Moreover, China's agriculture is in a period of transition from high dependence on agrochemical inputs and high resource consumption and environmental costs to an intensive production model that is more focused on the coordinated development of agricultural production, environmental protection, and resource use [10]. Thus, increasing vegetable production in a highly efficient manner is a challenge to China's modern agriculture. However, until now, quantitative studies on the ecological efficiency and sustainability of greenhouse vegetable production have been relatively rare.

A large number of methods have been used to evaluate the environmental consequences and sustainability of the agroecosystems, such as emergy analysis (EMA) [11–13], ecosystem service [14], and lifecycle assessment (LCA) [15,16]. Particularly, EMA and LCA are two widely used tools. EMA is an effective method used to analyze the ecological efficiency and sustainability of a production system considering natural environmental resources, information, labor, and services. However, it ignores environmental emissions. LCA is widely used to analyze the potential environmental impacts of a production processes. However, it ignores the contribution of natural resources and labor and services. The combined use of EMA and LCA can make up the two methods' respective shortcomings, and it is imperative to evaluate a production progress from a broader perspective [17]. Based on this thinking, some researchers have adopted this integrated approach to study the sustainability of agricultural ecosystems, such as wine supply chains [18], grain production systems [19], and intensive pig farming systems [20]. However, at present, few quantitative studies have been conducted on the overall sustainability of greenhouse vegetable production. In addition, studies on the sustainability of vegetable production systems under different fertilization modes are rarely reported. Economic analysis (ECA) reveals the cost and income of the analyzed system based on market value, which is another important aspect that cannot be ignored in promoting more sustainable production and consumption patterns.

Therefore, in this study, a consecutive four-season field experiment was taken as an example, including conventional (CON), low-input (LOW), and organic (ORG) greenhouse vegetable production modes in Quzhou County, Hebei Province, North China Plain. The main objective of this study was to evaluate the economic performance, resource use, and environmental impacts of the greenhouse vegetable production and screen optimal greenhouse vegetable production mode.

2. Materials and Methods

2.1. System Description

2.1.1. Study Area and Experimental Design

A long-term experiment for vegetable growth was conducted beginning in March 2002 at Quzhou Experimental Station of China Agricultural University [7]. The experiment site was located in the north of Quzhou County ($36^{\circ}52'$ N, $115^{\circ}01'$ E) in Handan City, Hebei Province, North China Plain. This area belongs to the temperate and semi-humid monsoon climate zone. It has abundant climate resources such as light, heat, and water, but is strongly affected by the monsoon. It is cold and dry in winter and spring, and warm and rainy in summer. The annual average temperature is 13.2 °C and the average annual rainfall is 604 mm, 70% of which occurs in July to September. The annual evaporation is 1841 mm. The tested soil was the salinized tidal cinnamon soil with a pH of 7.8. The average organic matter content in the cultivated layer (0–20 cm) was above 16.63 g kg⁻¹, total nitrogen (N) was 1.36 g kg⁻¹, and alkaline hydrolyzed N was 101.3 mg kg⁻¹. Available phosphorus and available potassium were 139.1 mg kg⁻¹ and 257.3 mg kg⁻¹, respectively [8].

The experiment consisted of organic (ORG), low-input (LOW), and conventional (CON) modes. Each mode had three semi-round arch greenhouses (52 m in length and 7 m in width for each greenhouse). Beginning in 2002, various vegetables were grown in different seasons, including tomato, cucumber, celery, fennel, cauliflower, and eggplant. The eggplant (Solanum melongena L.) and celery (Apium graveolens L.) were transplanted from March to August and October to February, respectively, and a four-year (2013–2016) experiment was conducted. Only the eggplant production was taken as a paradigm, and average values from entire four-year period were used for all input-output data. The CON mode adopted the traditional greenhouse management methods of local farmers, mainly using chemical fertilizers with a small amount of poultry manure. The pest control was mainly based on chemical methods. The LOW mode combined 50% of chemical fertilizers with 50% of poultry manure, using biological methods for general plant protection and low-toxic chemical pesticides for serious situation. Only poultry manure was used for ORG mode according to the International Federation of Organic Agriculture Movements (IFOAM), and biological and physical methods were used for pest control. The total N application rate was in the same level of all three modes (Table 1). The irrigation water was the same among different production modes with an irrigation method of flooding irrigation.

Item	Unit	CON	LOW	ORG
Nutrition				
Urea	kg N ha ^{−1}	661.1 ± 234.95	330.5 ± 117.5	-
P fertilizer	$kg P_2O_5 ha^{-1}$	758.4 ± 0.0	379.2 ± 0.0	-
K fertilizer	$kg K_2O ha^{-1}$	630.4 ± 0.0	315.2 ± 0.0	-
Poultry manure	kg N ha⁻¹	182.6 ± 33.4	366.5 ± 65.3	732.9 ± 130.6
Pesticide	kg ha ⁻¹	9.1 ± 4.0	3.8 ± 7.0	-
Fungicide	kg ha ⁻¹	2.1	2.1	-
Plastic ground cover	kg ha⁻¹	41.7	41.7	41.7
Diesel	kg ha ⁻¹	50.1	50.1	50.1
Irrigation	m^3 ha ⁻¹	9425.0	9425.0	9425.0
Electricity	kW h ha ⁻¹	6597.5	6597.5	6597.5
SOC sequestration	$kg CO_2 ha^{-1}$	2024.0	3960.0	12,037.7
Yield	t ha ⁻¹	117.2	122.1	139.3

Table 1. Inputs and outputs of different eggplant production modes per season.

SOC, soil organic carbon; Con, conventional mode; LOW, low-inputs mode; ORG, organic mode.

2.1.2. Sampling and Laboratory Analysis

Soil samples with three replicates per production mode were taken at 0–20 cm depth within 3–5 days after each irrigation during the growth period from 2013 to 2016. The soil organic matter was determined using the potassium dichromate digestion method [21]. Fresh soil samples were extracted with 2 mol L⁻¹ KCl to determine the concentrations of NH₄⁺-N and NO₃⁻-N using a continuous flow analyzer (AA-3, Bran and Luebbe, Norderstedt, Germany). The content of heavy metals (mainly considering Cu, Zn, Pb, and Cd) in soil samples was determined using ICP-MS (7700, Agilent, California, USA). For leachate quantification, nine lysimeters (one per replicate) were preinstalled at the site at a depth of ~1 m. The leachate was collected within 3–5 days after each irrigation and the volume was recorded. Leaching samples were analyzed for TN, $NO_3^{-}N$, and $NH_4^{+}N$ by a flow analyzer (AA-3, Bran and Luebbe, Norderstedt, Germany). The phosphorus was digested with potassium persulfate and determined by Spectrophotometer (UV-2800, UNICO, Shanghai, China). The venting method was used to determine the NH₃ emission by Wang et al. [22]. N₂O fluxes were sampled and determined using the static chamber-gas chromatographic (7890, Agilent, California, USA) method [23]. At the harvesting time, eggplants were picked by hand and weighed with three replicates. Details of each measurement procedure can be found in the literature [9,24]. On-field releases of different eggplant production modes per season are shown in Table 2.

Environmental Medium	Unit	Items	CON	LOW	ORG
Air	kg ha ⁻¹ kg ha ⁻¹	N ₂ O NH ₂	20.97 105.46	16.52 87.13	12.84 91.61
Water	kg ha ⁻¹	NO ₃ ⁻	248.09	205.61	218.03
	kg ha ⁻¹	Cd	0.004	0.009	0.017
Soil	kg ha ⁻¹ kg ha ⁻¹	Pb Cu	0.060 0.443	0.121 0.890	0.242 1.780
	$kg ha^{-1}$	Zn	1.573	3.157	6.314

Table 2. On-field releases of different eggplant production modes per season.

2.2. Economic Analysis (ECA)

During the experiment period, the prices of all the inputs and outputs were recorded. In this study, the cost of eggplant production mainly included chemical fertilizer, poultry manure, pesticides, fungicides, electricity, diesel, agricultural ground cover, and direct labor. Total income refers to the output value of eggplant production. A simple economic cost-benefit analysis was conducted in this study, and several economic indices were selected to evaluate the economic performance of different vegetable production modes (Table 3). These indices are economic profits and value to cost ratio, which are commonly used to characterize the economic characteristics of agroecosystems [25].

2.3. Emergy Analysis (EMA)

Emergy is defined as the sum of the available energy required indirectly and directly to make a product or provide service [26]. The first step of EMA is to define the boundaries of the research system by Odum [26]. Figure 1 shows the emergy flows and energy sources driving the production process. Then, all energy sources were categorized into three types, which include free local renewable resources (L_R), free local nonrenewable resources (L_N), and economically imported resources (F), based on the definition of Xu et al. [25]. We divided emergy input into renewable and nonrenewable parts through renewability factor (RNF). The energy conversions of all products were derived from Luo [27]. All the inputs were converted into emergy by multiplying the inputs by suitable unit values (UEVs), as described by Equation (1).

$$Emergy = \sum_{i=1}^{i=n} UEV_i \times f_i \quad i = 1, 2, \dots, n,$$
(1)

where Emergy denotes solar emergy; f_i denotes *i*th input flow of matter, energy or service; and UEV_i denotes unit emergy value of the *i*th flow.

Indices	Units	Expression ^b	Explanation
Economic analysis			
Economic profits	$_{\rm Ha^{-1}}$	Income-cost	Economic benefits of product on unit land
Value to cost Ratio (VCR)	NA	Income/cost	Economic benefits of vegetable production system
Emergy analysis			
Unit emergy value (UEV)	sej J ⁻¹	U/Y	The unit emergy value of the production system.
Renewable fraction (%R)	%	$100\times(\mathrm{L}_{\mathrm{R}}+\mathrm{F}_{\mathrm{R}})/\mathrm{U}$	The ratio of renewable resources to total resources in a production system
Emergy yield ratio (EYR)	NA	U/F	The ability of the system to make available local resources by investing outside resources
Environmental loading ratio (ELR)	NA	$(\mathrm{L}_{\mathrm{N}}+\mathrm{F}_{\mathrm{N}})/(\mathrm{L}_{\mathrm{R}}+\mathrm{F}_{\mathrm{R}})$	Environmental pressure resulting from the system
Emergy sustainability index (ESI)	NA	EYR/ELR	Sustainability of the system
Life cycle assessment ^a			
Potential environmental impact index	NA	$\sum E_{p(x)}/S_{(2000)}W_x$	Environmental impacts on unit area

 Table 3. Expression and explanation of the assessment indices.

^a $E_{p(x)}$ is the characterization result of the system's impact on the x-aspect, $S_{(2000)}$ is benchmarks in 2000, W_x is weight factors of potential environmental impacts. ^b U: Total emergy inputs; Y: Yield, i.e., the product generated by a process. L_R or L_N: Free local renewable or nonrenewable resources; F: Economic or purchased resources; F_R or F_N: Renewable or nonrenewable fractions of purchased resources.



Figure 1. Energy diagram of the vegetable production system. \square indicates system boundary;

indicates energy source; indicates; indicates producer; indicates heat sink; indicates storage tank.

Finally, several emergy-based indices were selected to evaluate the production efficiency and the resource use of different vegetable production modes (Table 3). The inputs and outputs were converted into emergy units based on the planetary baseline of 1.20×10^{25} sej year⁻¹ [28].

2.4. Lifecycle Assessment (LCA)

The system boundary of this study was taken from the production of agricultural materials to vegetable cultivation. The Functional Unit (FU) analyzed was 1 t harvested eggplant with the objective

of achieving the lowest emissions and resource use per unit of yield. The system boundary and FU were kept the same between the LCA and EMA methods. On-field emissions were calculated from field measurements and simulation of local models (Table 2; [29,30]). The percentage of pesticides remaining in the air, water, and soil were 10.0%, 1.0%, and 43.0%, respectively [31]. Emissions on the combustion of diesel came from Reference [30]. The data of infrastructure, such as steel and concrete, were excluded because they were not available. The lifecycle inventory was processed and interpreted in terms of environmental impacts, involving characterization, normalization, and weighting [32,33]. The CML2001 method [34] was selected, and six environmental impact categories closely related to agricultural production were selected for this study, namely global warming potential (GWP) (100 years), acidification potential (AP), eutrophication potential (EP), aquatic ecotoxicity (AT), human toxicity (HT), and terrestrial ecotoxicity (TT). This study used normalization factors of the global per-person environmental impact for 2000 [35]. Moreover, weight factors were from Wang et al. [36]. The calculation of potential environmental impact index is shown in the Table 3.

3. Results

3.1. Economic Performance

Table 4 shows the cost, income, economic profit, and value to cost ratio of three eggplant production modes. The costs of CON, LOW, and ORG were 23.2 thousand \forall ha⁻¹, 26.0 thousand \forall ha⁻¹, and 17.6 thousand \forall ha⁻¹. The cost of ORG mode was 24% and 32% lower than that of CON and LOW, respectively. However, the income of ORG mode increased by 16% and 12% compared with of CON and LOW, respectively. The ORG mode had the highest economic profit of 818.2 thousand \forall ha⁻¹, followed by CON (679.9 thousand \forall ha⁻¹) and LOW (706.6 thousand \forall ha⁻¹). The profit of ORG mode increased by 17% and 14% compared with that of the CON and LOW modes, respectively. The VCR of ORG mode was 36% and 41% higher than that of CON and LOW, respectively.

Item	Unit	CON	LOW	ORG
Cost	10^3 ¥ha ⁻¹	23.2	26.0	17.6
Income	10^3 ¥ha ⁻¹	703.2	732.6	835.8
Economic profit	$10^{3} { m ~Yha^{-1}}$	679.9	706.6	818.2
Value to cost ratio (VCR)	-	30.3	28.2	47.6

Table 4. The economic indices of different eggplant production modes.

Figure 2 shows the cost structure of the three eggplant production modes considering direct labor inputs. The cost structure of fertilizer among three production modes varied due to different fertilizer use. ORG mode had the single largest cost of poultry manure (8566 \pm ha⁻¹), while the cost of chemical fertilizer was zero. The electricity cost of three modes was the same, with the value of 5608 \pm ha⁻¹, accounting for, as a share of total input costs, 24% for CON, 22% for LOW, and 32% for ORG. The cost of ground cover accounted for 13%, 12%, and 17% of the total costs of CON, LOW, and ORG, respectively. The cost of diesel was the lowest with the value of 400 \pm ha⁻¹. The cost of direct labor was the same with the value of 4500 \pm ha⁻¹. In total, shifting cultivation modes from CON and LOW to ORG resulted in an obvious reduction in the use of chemical fertilizer.

Investment ($\frac{1}{4}$ ha⁻¹)



Figure 2. Cost structure of the three vegetable production modes considering direct labor inputs.

3.2. Resource Use

Table 5 shows the emergy calculation process and Table 6 shows the aggregate emergy flows of the three eggplant production modes. The total emergy use (U) of CON, LOW, and ORG modes were 7.65×10^{14} sej t⁻¹ season⁻¹, 6.15×10^{14} sej t⁻¹ season⁻¹, and 3.90×10^{14} sej t⁻¹ season⁻¹, respectively, suggesting that ORG mode greatly decreased the resource consumption compared to CON and LOW. Local natural resources (L) only accounted for 10.2%–17.0% to U of different production modes. The three production modes were mainly composed of economic imported resources (83.0%–89.8%) and nonrenewable emergy flows (62.8%–79.4%), indicating that the greenhouse vegetable production is unsustainable in the long run.

Figure 3 shows the emergy inputs structure of different eggplant production modes. Of all the emergy inputs, chemical P fertilizer application of CON mode was the highest with the value of 2.26×10^{14} sej t⁻¹, whereas the values of the LOW and ORG modes decreased greatly. The emergy use of electricity was large, with values of 1.53×10^{14} sej t⁻¹, 1.47×10^{14} sej t⁻¹, and 1.29×10^{14} sej t⁻¹ for CON, LOW, and ORG, respectively. The emergy use of labor and service was also large, with values of 1.06×10^{14} sej t⁻¹, 1.11×10^{14} sej t⁻¹, and 8.10×10^{13} sej t⁻¹ for CON, LOW, and ORG, respectively. The total emergy, suggesting that the production of greenhouse vegetable depends on the labor activities. In the North China Plain, the groundwater is the most principal agricultural irrigation water. The emergy use of groundwater for CON, LOW, and ORG were 7.38×10^{13} sej t⁻¹, 7.08×10^{13} sej t⁻¹, and 6.21×10^{13} sej t⁻¹, respectively, with the proportion of 10%-16% to the total emergy inputs. Other items had relatively minor impacts to the total emergy use.

No. Items	Tt	T		Raw Data		DNIE		Emergy (sej)			
	Units	CON	LOW	ORG	KNF	CON	CON	LOW	ORG		
Inputs											
1	Sun	J	1.60×10^{11}	1.53×10^{11}	$1.34 imes 10^{11}$	1.00	1.00	1.60×10^{11}	1.53×10^{11}	$1.34 imes 10^{11}$	
2	Ground water	J	3.97×10^{8}	3.81×10^{8}	3.34×10^{8}	0.10	1.86×10^{5}	7.38×10^{13}	7.08×10^{13}	6.21×10^{13}	
3	Seed	J	1.34×10^{5}	1.28×10^5	1.12×10^{5}	1.00	8.41×10^4	1.12×10^{10}	1.08×10^{10}	9.45×10^{9}	
4	Urea	g	1.22×10^4	5.86×10^{3}	0.00	0.00	4.84×10^9	$5.91 imes 10^{13}$	2.83×10^{13}	0.00	
5	Phosphorus	g	4.56×10^{4}	2.19×10^4	0.00	0.00	4.97×10^{9}	2.26×10^{14}	1.09×10^{14}	0.00	
6	Potassium	g	1.05×10^4	5.06×10^{3}	0.00	0.00	1.40×10^{9}	1.48×10^{13}	7.10×10^{12}	0.00	
7	Manure	Ĵ	2.99×10^{8}	5.75×10^{8}	1.01×10^{9}	0.68	2.05×10^4	6.12×10^{12}	1.18×10^{13}	2.07×10^{13}	
8	Pesticide & Fungicide	g	9.56×10^{1}	4.83×10^1	0.00	0.00	1.89×10^{10}	1.81×10^{12}	9.13×10^{11}	0.00	
9	Ground cover	¥	2.56×10^{1}	2.46×10^{1}	2.15×10^1	0.00	7.54×10^{11}	1.93×10^{13}	1.85×10^{13}	1.62×10^{13}	
10	Diesel	g	4.27×10^2	4.10×10^2	3.60×10^2	0.05	8.41×10^4	3.60×10^{7}	3.45×10^7	3.02×10^{7}	
11	Electricity	J	7.04×10^{8}	6.75×10^{8}	5.92×10^{8}	0.81	2.18×10^{5}	1.53×10^{14}	1.47×10^{14}	1.29×10^{14}	
12	Service	¥	1.60×10^{2}	1.76×10^{2}	9.39×10^{1}	0.05	7.54×10^{11}	1.21×10^{14}	1.33×10^{14}	7.08×10^{13}	
13	Labor	J	1.58×10^7	1.55×10^{7}	1.59×10^{7}	0.10	5.73×10^{6}	$9.04 imes 10^{13}$	8.87×10^{13}	9.13×10^{13}	
Total		-						7.22×10^{14}	5.39×10^{14}	3.66×10^{14}	
Outputs											
14	Eggplant yield	g	1.00×10^{6}	1.00×10^{6}	1.00×10^{6}			7.65×10^{8}	6.15×10^{8}	3.90×10^{8}	
15	Eggplant yield	Ĵ	1.05×10^6	1.05×10^6	1.05×10^{6}			7.29×10^8	$5.85 imes 10^8$	3.71×10^8	

RNF, renewability factor.

Aggregate Emergy Flows	CON	%	LOW	%	ORG	%
Local natural resources (L)	7.39×10^{13}	10.2%	7.10×10^{13}	13.2%	6.22×10^{13}	17.0%
Local renewable natural resources (L_R)	7.54×10^{12}	1.0%	7.23×10^{12}	1.3%	6.34×10^{12}	1.7%
Local nonrenewable natural resources (L _N)	6.64×10^{13}	9.2%	6.37×10^{13}	11.8%	5.59×10^{13}	15.3%
Economic imported resources (F)	6.91×10^{14}	89.8%	5.44×10^{14}	86.8%	3.28×10^{14}	83.0%
Renewable economic imported resources (F _R)	1.43×10^{14}	19.5%	1.43×10^{14}	25.8%	1.31×10^{14}	35.5%
Nonrenewable economic imported resources (F _N)	5.48×10^{14}	70.2%	4.01×10^{14}	61.1%	1.97×10^{14}	47.5%
Renewable emergy flows (L_R+F_R)	1.51×10^{14}	20.6%	1.50×10^{14}	27.1%	1.37×10^{14}	37.2%
Nonrenewable emergy flows (L _N +F _N)	6.15×10^{14}	79.4%	4.65×10^{14}	72.9%	2.53×10^{14}	62.8%
Total emergy input (U)	7.65×10^{14}	100%	6.15×10^{14}	100%	3.90×10^{14}	100%



Figure 3. Emergy inputs structure (sej t^{-1}) of the three vegetable production modes.

Table 7 shows the emergy-based indices for different eggplant production modes. The unit emergy values (UEV) of CON, LOW, and ORG were 7.29×10^8 sej J⁻¹, 5.85×10^8 sej J⁻¹, and 3.71×10^8 sej J⁻¹, respectively. This indicates that the production efficiency of ORG mode increased by 49% and 37% compared with that of CON and LOW, respectively. Renewable fraction (%R) reflects the renewability of resource utilization in a production system. The %R of ORG increased by 43% and 31% compared with that of CON and LOW, respectively. The emergy yield ratios (EYR) of CON, LOW, and ORG were 1.11, 1.13, and 1.19 respectively, showing that ORG has the biggest ability to exploit local resources among the three modes. Environmental loading ratio (ELR) can be used as a measure of ecosystem stress caused by production activity. The ELRs of CON, LOW, and ORG were 4.08, 3.10, and 1.84, respectively, with ELR of ORG decreasing by 55% and 41% compared with the other two modes. This indicates that CON exerts high pressure on the local environment, whereas ORG can relieve the pressure on the environment. Emergy sustainability index (ESI) can be used to characterize the overall sustainability of a production system: The higher the ESI, the better the system's sustainability. The ESIs of CON, LOW, and ORG were 0.27, 0.36, and 0.65, respectively, and the ESI of ORG was

65% and 45% higher than that of CON and LOW. The above results show that the environmental sustainability of CON is the worst, whereas the ORG is beneficial to increase system sustainability.

Emergy	Unit	CON	LOW	ORG
Unit emergy value (UEV)	$10 \times 10^7 \text{ sej J}^{-1}$	7.29	5.85	3.71
Renewable fraction (%R)	%	20	24	35
Emergy yield ratio (EYR)	-	1.11	1.13	1.19
Environmental loading ratio (ELR)	-	4.08	3.10	1.84
Emergy sustainability index (ESI)	-	0.27	0.36	0.65

Table 7. The emergy indices of different eggplant production modes.

3.3. Environmental Impacts

Table 8 shows the LCA results of characterization, normalization, and weighted evaluation results of three eggplant production modes. For characterization results, the GWP, AP, and EP of ORG mode for 1 t eggplant was 15.1 kg CO₂-eq, 3.3 kg SO₂-eq, and 0.5 kg PO₄-eq, respectively, decreasing by 92%, 27%, and 29% compared to CON and by 87%, 13%, and 17% compared to LOW. The characterized results of AT, HT, and TT for ORG were 21.4 kg 1,4-DCB-eq, 17.9 kg 1,4-DCB-eq, and 1.6 kg 1,4-DCB-eq, decreasing by 59%, 92%, and 54% compared to CON and by 41%, 83%, and 27% compared to LOW.

Table 8. Environmental indices of different eggplant production modes.

Categories	Unit	Characterization Results Normalization Results			Results	ults Weighted Evaluation Results				
		CON	LOW	ORG	CON	LOW	ORG	CON	LOW	ORG
GWP	kg CO ₂ -eq	179.7	117.1	15.1	0.0262	0.0170	0.0022	0.0031	0.0020	0.0003
AP	kg SO ₂ -eq	4.5	3.8	3.3	0.0854	0.0735	0.0624	0.0120	0.0103	0.0087
EP	kg PO ₄ -eq	0.7	0.6	0.5	0.3674	0.3024	0.2431	0.0441	0.0363	0.0292
HT	kg 1,4-DCB-eq	51.7	36.2	21.4	0.2620	0.1835	0.1084	0.0367	0.0257	0.0152
AT	kg 1,4-DCB-eq	222.7	103.1	17.9	46.1138	21.3407	3.7043	5.0725	2.3475	0.4075
TT	kg 1,4-DCB-eq	3.5	2.2	1.6	0.5780	0.3558	0.2615	0.0520	0.0320	0.0235
Total								5.22	2.45	0.48

GWP, global warming potential; AP, acidification potential; EP, eutrophication potential; HT, human toxicity; AT, aquatic ecotoxicity; TT, terrestrial ecotoxicity.

The significance of the normalized results allows us to compare the relative magnitude of the different kinds of potential environmental impacts. Of all the six impact categories, the results of AT were the highest, indicating that AT was the largest environmental impact of the systems, followed by TT. Compared with CON and LOW, the normalized AT and TT of ORG declined by 83%–92% and 27%–55%, respectively.

The total weighted evaluation results can reflect the overall potential environmental impact of the three vegetable production modes. The total potential environmental impact index was 5.22, 2.45, and 0.48 for CON, LOW, and ORG, respectively. The results suggest that CON results in more environmental pollution than the other two modes, and ORG mode is a relatively environmentally friendly production mode.

The hotspot of potential environmental impacts of different eggplant production modes is shown in Figure 4. When soil organic carbon (SOC) changes were accounted for while computing the GWP, differences in GWPs were observed for different eggplant production modes. The negative SOC values represented atmospheric CO₂ sink, accounting for 8%, 18%, and 46% to the total GWP of CON, LOW, and ORG, respectively. This suggests that ORG mode contributes to the mitigation of climate change. The electricity was found to be a hotspot, accounting for 27%–32% of GWP, 57%–65% of AP, and 38%–77% of HT across different modes, respectively. The urea application contributed large to GWP (14%–25%), AP (5%–9%), EP (6%–10%), and HT (38%–55%) for CON and LOW production modes. However, for ORG mode, the application of poultry manure constituted additional 20% to HT and 42% to AT, respectively. On-field emission (as denoted in Table 2) was an important pollution source to the GWP, AP, EP, AT, and TT. For example, it had a large contribution of 85%–92% to EP, 42%–95% to AT, and 86%–92% to TT. Other inputs had relatively minor impacts.



Figure 4. Hotspots of potential environmental impacts of the three vegetable production modes. (a) Conventional mode; (b) Low-input mode; (c) Organic mode.

4. Discussion

4.1. Economic Analysis of Cultivation Shifting from Conventional to Organic Mode

Vegetable production can provide humans with vegetable products and maintain human survival and health, and vegetables as a kind of cash crop can also promote the employment of agricultural labor. Different researchers hold different views on the sustainability of organic agriculture [37,38]. One of the main reasons is that the yield of organic agriculture is lower than that of conventional agriculture, especially in the early period of the conversion from conventional agriculture to organic agriculture. In this study, the eggplant yield of ORG was 139.3 t ha⁻¹, which was 16% and 12% higher than that of the CON and LOW modes, respectively. This may be due to the high amount of manure input in organic mode in this study [9]. Regarding the economic performance, the economic profits of ORG increased by 14%–17% compared with that of CON and LOW modes, and the value to cost ratio of ORG was much higher (36%–41%) than the other two modes. This was mainly due to the reduced cost of a large number of chemicals (such as fertilizers and pesticides) and higher yields in ORG. Although the organic agriculture requires a large amount of manure, its price is much cheaper than that of chemical fertilizers, and the use of manure is also conducive to the development of regional circular agriculture, because they mainly come from livestock manure. Regarding the cost structure, the high cost of electricity for irrigation accounted for 24%–32% of the total operating cost mainly due to the flooding irrigation method. In the future, irrigation methods need to be optimized, such as adopting drip irrigation, to save agricultural water and further increase the economic profits for farmers.

4.2. Sustainability Evaluation of Cultivation Shifting from Conventional to Organic Mode

In recent years, China has pursued sustainable agriculture with the multi-objective coordinated development of high agricultural yield, resource efficiency, and environmental soundness. The holistic evaluation of the sustainability of agricultural production is the basis for achieving this goal. Previous studies on vegetable production mainly focused on a certain aspect of the environmental

impacts [4,15,39]. It was reported that the total potential environment impact index of organic tomato cultivation in Beijing is 0.40 [39], which is close to organic eggplant production (0.48) found in this research. In this study, to increase understanding of the production efficiency and sustainability of cultivation shifting from conventional to organic mode, the EMA and LCA approaches were applied. The results showed that the production efficiency of ORG increased by 37%–49% than that of the CON and LOW modes. ORG greatly reduced the consumption of nonrenewable resources and increased the renewability of resource utilization by 31%–43% in eggplant production systems. The three greenhouse vegetable production modes are mainly driven by economic imported resources (83.0-89.8%) and nonrenewable resources (62.8–79.4%) by energy analysis, namely chemical fertilizer and electricity. China's fertilizer industry is different from foreign countries. For example, the synthetic ammonia of N fertilizer industry in China mainly depends on coal, thus resulting in high energy consumption and environmental pollution [40]. Similarly, the electricity used for irrigation is primarily derived from coal. Therefore, organic greenhouse vegetable cultivation can help protect nonrenewable resources and mitigate climate change. [41]. Moreover, ORG mode increased the ESI by 45%–65%, and decreased the potential environmental impacts by 80%-91% compared with the other two modes. These results show that ORG not only saves nonrenewable resources (such as chemical P and K fertilizers) and improves production efficiency, but also reduces the environmental burden.

In this study, the emergy of service was 1.21×10^{14} , 1.33×10^{14} , and 7.08×10^{13} sej t⁻¹ season⁻¹ for CON, LOW, and ORG mode, respectively. ORG mode greatly decreased the need of service by 41% and 47% compared with the other two modes, mainly because ORG did not involve using externally purchased chemical fertilizers, electricity, or ground cover. The emergy of manure only accounted for 1%–5% to the total emergy use of the three production modes. In addition, Figure 4 shows great reduction advantages of greenhouse gas of manure compared with chemical fertilizer. However, the emissions associated with poultry production that were the source of the manure remains unknown. Thus, this potential downside to sourcing fertility from manure should be explored in the future. In order to further increase the system's production efficiency and reduce external purchased resources, regional circular agriculture should be developed. For example, "waste" (such as animal manure) or litter from livestock and poultry industry could be included in the vegetable production system. However, this requires a systematic assessment of multiple industries from a broader perspective in the future.

5. Conclusions

Long-term organic vegetable cultivation greatly increased vegetable yields and was beneficial to increase farmers' income. Organic mode can not only decrease nonrenewable resource use and negative environmental impacts, but also increase production efficiency and overall system sustainability compared with conventional and low-input modes. Thus, organic planting is a promising strategy for greenhouse vegetable cultivation in the North China Plain.

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