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Economic benefits and soil improvement: Impacts of vermicompost use in spinach production through industrial symbiosis

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A B S T R A C T

Industrial symbiosis is being increasingly recognized as a valuable tool for promoting a more sustainable production process in agriculture. However, the primary motivation for implementing industrial symbiosis is economic viability. In the context of industrial symbiosis, by linking agriculture and food together, the study examines the impact of the use of vermicompost, derived from agricultural by-products, on spinach yield as well as on nutritional and biochemical soil aspects. Moreover, the economic feasibility for spinach farmers is also investigated. A field experiment with five treatments i) solarization ii) solarization and vermicompost iii) green manure and solarization iv) green manure, solarization, and vermicompost, and v) vermicompost has been realized in "Piana del Sele", a rural area in Southern Italy. Collected data have been analysed through a Partial Least Square Structural Equation Modeling approach to assess the overall impact (direct and indirect effects) of vermicompost on both spinach yield and soil characteristics. Lastly, the economic profitability of using vermicompost is pointed out for spinach growers. The study findings show that the highest positive impact on yield occurs when vermicompost is combined with solarization (+15 %). Moreover, with regard to soil characteristics, the combination of vermicompost and solarization has a positive impact on nutrients, fungal biodiversity, and the biochemical quality of the soil. The economic profitability of using vermicompost in conjunction with solarization is guaranteed when the price of vermicompost is below € 0.84/kg. In light of these findings, some policy interventions can be implemented to enable industrial symbiosis as a viable tool for a circular economy in the agri-food sector. These include promoting the diffusion of biogas plants to valorize agricultural by-products and promoting the use of vermicompost in farms, by encouraging its purchase by farmers.

1. Introduction

The European agricultural sector is estimated to produce approximately 700 million tons of waste per year [1], resulting in billions of euros lost in waste management [2]. This leads to a significant loss of valuable compounds and nutrients and contributes to environmental pollution. In response to the scarcity of natural resources and the pressing demand for sustainability in the agri-food sector, there is a growing effort to minimize and utilize waste [1].

The bio-economy, defined as the use and production of biological resources to create products, processes, and services across all industries and trades in a sustainable manner [3], plays a crucial role in transforming agricultural waste into valuable products.

The potential of the bio-economy can be strengthened through the integration of the Circular Economy (CE) approach. The CE aims to eliminate the concept of waste by promoting the use, reuse, and recycling of resources [4]. The combination of CE and bio-economy has given rise to a new concept called the Circular Bio-Economy (CBE), where biomass is first used for material purposes and then utilized in multiple steps to reduce waste [5]. The European Commission recognizes the Bioeconomy Strategy and the Circular Economy Action Plan as effective tools for promoting sustainability in renewable bio-based materials [6]. They also identify Industrial Symbiosis (IS) as the operational tool for implementing the circular bio-economy in Europe. IS has its roots in biology, where symbiosis is defined as a relationship between individuals of different species for mutual benefit [7]. According to Neves and colleagues (2020), the benefits of IS are not only environmental but also social and economic [8]. Chertow [9] defined IS as the

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collaboration between separate industries with the goal of gaining a competitive advantage, involving the physical exchange of materials, energy, water, and by-products.

Recently, some researchers have given IS a more comprehensive vision, identifying its multiple roles, such as saving resources, providing economic benefits, reducing greenhouse gas emissions, protecting natural resources, and reducing waste [10]. In other words, IS is viewed as an eco-innovative system based on circular economy and industrial ecology concepts [11]. A review of IS [8] reveals a diverse range of case studies, in terms of location, type of industries involved in the symbiosis, and methods used for analysis [8]. Research on IS has been conducted globally, with the highest concentration in China [8]. Although the manufacturing sector is the most prominent activity in the synergies, agriculture, forestry, and fishing are also considered. Hamam and colleagues (2023) found that the number of publications on IS in the agri-food sector is increasing, with a prevalence of case studies analyzing the motivations that drive stakeholders to establish an industrial symbiosis (Patrizio et al., 2018; [12]), or quantifying the environmental benefits of its application [13]. However, despite the fact that economic viability is the main driver of IS implementation [8], there is a lack of empirical studies quantifying the economic impact of such synergies in the agri-food sector. The current study adds to the scientific literature by analyzing the economic benefits of an IS implemented in a specific rural area in Southern Italy, for downstream actors (i.e. farmers). The novelty of this study rests not only in its economic feasibility analysis of an industrial symbiosis but also in assessing the vermicompost's effects on spinach cultivation and soil characteristics, thereby defining its economic profitability for farmers. Specifically, the study aims to investigate the economic feasibility, in terms of crop yield, by using vermicompost, a soil enhancer produced from the anaerobic digestion of a mixture of buffalo slurry, olive mill wastewater, and milk whey, for spinach cultivation. Existing research has explored various aspects of using vermicompost in agriculture. Studies have compared its efficacy with alternatives like neem cake and vermiwash in spinach cultivation (Salma and Hossain, 2021; [14]) and examined its impact on soil quality [15]. Additional work has addressed the factors influencing its adoption by farmers [16] and its economic profitability, particularly in broccoli and strawberry farming [17,18]. However, there is a research gap concerning the effects of this specific type of vermicompost—derived from a blend of buffalo slurry, olive mill wastewater, and milk whey—on spinach yield and soil quality.

The effects of vermicompost on spinach production and soil quality will be evaluated by quantifying the monetary value for farmers after using vermicompost (both alone and in combination with other soil treatments). Moreover, a sensitivity analysis will show the economic profitability of using vermicompost by defining its threshold price. Overall, this study will provide valuable results on the economic feasibility of industrial symbiosis, contributing to the promotion of the circular bio-economy in the agri-food sector.

2. Materials and method

2.1. Study area and problem statement

The site where the study is conducted and where the potential industrial symbiosis is being investigated is located in the "Piana del Sele", an alluvial plain located in Southern Italy, 80 km south of Naples. It covers 50,951 ha, or 3.7 % of the Campania region [19]. The primary sector is the main source of income for the region. The study site is a productive area, with 4800 ha of land cultivated under greenhouses, 12 % of which are organic farming. Fresh-cut vegetables produce over 380 million euros annually, with a strong focus on exports to European and world markets. However, the intensive agricultural activity of growing fresh-cut vegetables in greenhouses results in the loss of soil fertility due to the mineralization of organic matter [20] and degradation of soil structure [21]. Thus, the main challenge for farmers is to preserve the fertility of the soil by maintaining its structure, organic matter content, biological activity, and controlling root pathogens.

The "Piana del Sele" area is also home to 311 buffalo farms, with a total of 67,288 buffalos, or 16% of the national total (ISTAT, 2021; http://dati.istat.it/Index.aspx). These farms produce a large amount of livestock manure and milk whey as a by-product of mozzarella production. Fresh manure is not suitable for fresh-cut vegetable cultivation due to strict rules, such as the absence of *Salmonella* and *E. coli* pathogens, but it can be used as fertilizer for other crops or combined with olive mill wastewater and used in anaerobic digestion plants for energy production. The anaerobic digestion process produces two by-products: a liquid and a solid digestate. The liquid fraction is deammonified, while the solid fraction is aerobically composted and fed to earthworms to produce vermicompost. Vermicompost is pathogen-free, non-toxic, rich in organic matter and nutrients, and therefore suitable for improving soil fertility and structure in greenhouses.

An industrial symbiosis between anaerobic digestion plants, mills, livestock/dairy farms, and fresh-cut vegetable farms could help promote a circular bio-economy process in an area with a strong agricultural and livestock tradition. The study will assess the economic benefits (in terms of crop yield) for spinach producers to promote the creation of industrial symbiosis for economic and environmental sustainability. Additionally, the effect of vermicompost on the biochemical and microbiological quality of soil will also be investigated.

2.2. Experimental design

The field experiment was conducted in a greenhouse farm of "Piana del Sele" from April 2020 to February 2021. Since 2017, the farm has been cultivating organic spinach, using soil solarization, green manure with Brassicaceae to control nematodes, and an average of four rototilling treatments per year. Organic amendments, including vermicompost made from solid digestate, deriving, in turn, from buffalo slurry, olive mill wastewater, and milk whey (C&F Energy Capaccio, Italy), and/or Brassicaceae green manure, were used. The physical, chemical, and biological properties of the vermicompost are outlined in Table 1. Five treatments were implemented in the experiment: solarization (SOL), solarization and vermicompost (SOL+VC), green manure and solarization (GM+SOL), green manure, solarization, and vermicompost (GM+SOL+VC), and vermicompost (VC).

A greenhouse area of approximately 3000 square meters was selected for the study and divided into 12 plots (2 plots per each of the five treatments, and 2 plots as control). For each plot 6 soil samples and spinach yields have been collected, thus generating an overall 72 observations. The field experiment began with the sowing of Brassicaceae at the end of April 2020, followed by the application of green manure in May 2020. The solarization of the plots was conducted in July 2020, and vermicompost (VC) was applied in September 2020. Soil samples were taken one week later in October 2020. The study involved two cycles of

Table 1
Physical, chemical and biological properties of vermicompost.

Properties	Mean ± Std.err
Moisture %	52.4 ± 6.0
pH	7.8 ± 0.3
EC dS m^{-1}	3.4 ± 0.4
Ash %	32.0 ± 1.7
N %	3.6 ± 0.2
C %	46.9 ± 1.6
H %	6.7 ± 0.1
S %	1.3 ± 0.1
O %	41.6 ± 1.6
C/N	13.1 ± 1.1
P_{tot} g kg^{-1}	11.9 ± 0.6
P Olsen g kg^{-1}	3.3 ± 0.1
E. coli, CFU g^{-1}	n.d.

spinach (*Spinacia oleracea*) cultivation, with spinach yields being harvested at the end of each cycle and the amount of commercial production being quantified for all experimental plots (Fig. 1). Soil samples were placed in polyethylene bags, sieved to remove particles larger than 2 mm, and air-dried at room temperature for chemical analysis or stored at 4 °C for biochemical analysis and at −18 °C for microbiological analysis (Fig. 1).

Table 2 shows all chemical, biochemical and microbiological soil parameters collected to assess the effect of VC (alone as well as combined with other treatments) on soil properties.

2.3. Statistical analysis

Several statistical analyses were conducted to examine the impact of vermicompost on spinach yield grown in greenhouses and the effect of vermicompost on soil quality. Firstly, a multi-way ANOVA followed by a Tukey post-hoc test was carried out to determine whether vermicompost, alone or in combination with other soil treatments, had a positive effect on spinach yield and soil quality. As for soil quality parameters, organic carbon is included in the analysis. Moreover, an Exploratory Factor Analysis (EFA) was performed to synthesize all other soil parameters collected. The EFA, which uses an orthogonal (Varimax) rotation, was used to identify the most relevant soil characteristics (or latent constructs) and to reduce the number of variables by exploring the correlations among soil parameters [33]. Soil parameters with a factor loading lower than |0.4| or those that were not correlated with each other were not considered. Moreover, in order to understand the mechanisms of action of vermicompost (both alone and in combination with other treatments) on spinach yield, a partial least squares structural equation model (PLS-SEM) has been employed. This approach was developed in line with the algorithm provided by Wold [34] and Lohmöller [35]. PLS-SEM is used to model relationships between latent and single-item observed variables and consists of three sequential stages [36]. Firstly, the scores of latent variables are estimated, then the measurement model parameters (weights/loadings) are estimated using the obtained scores, and finally structural model parameters (path coefficients) are estimated using the ordinary least squares method. The PLS-SEM algorithm is considered to provide sound estimates when using small sample sizes and non-normally distributed data [37,38]. The composite reliability was used to evaluate the internal consistency of the construct measures, and the convergent and discriminant validity of the construct was assessed. The convergent validity is achieved when each

Table 2
Chemical, biochemical and microbiological soil parameters collected.

Soil parameter	Method of determination	Reference
pH	1:2.5 soil:water suspension	[22]
Electrical conductivity (EC)	1:5 soil:water suspension	
Cation exchange capacity (CEC	Barium chloride and triethanolamine solution at pH 8.2	
Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	Flame atomic absorption spectrometry	
Assimilable Phosphorus	Bicarbonate extraction	
Total organic C	Elemental Analyser - UNICUBE®	[23]
Total Nitrogen	Elemental Analyser - UNICUBE®	
Microbial biomass carbon (MBC)	Chloroform fumigation/extraction method	[24]
Microbial biomass nitrogen (MBN)		
Dehydrogenase (DH)	Tetrazolium salts (TTC) solution	[25]
β-glucosidase	*p*-nitrophenyl-β-d-glucopyranoside (p-NG) substrate	[26]
Alkaline phosphatase	*p*-nitrophenyl phosphate (p-NPP) substrate	[27]
Acid phosphatase	*p*-nitrophenyl phosphate (p-NPP) substrate	[28]
Fluorescein diacetate hydrolysis (FDA)	Fluorescein diacetate substrate	[29]
Urease activity (UR)	Urea substrate	[30]
Basal respiration (CO_2)		[31];
Bacterial biodiversity	16S Rrna gene sequencing	[32]
Fungal biodiversity	ITS1-2 sequencing	[32]

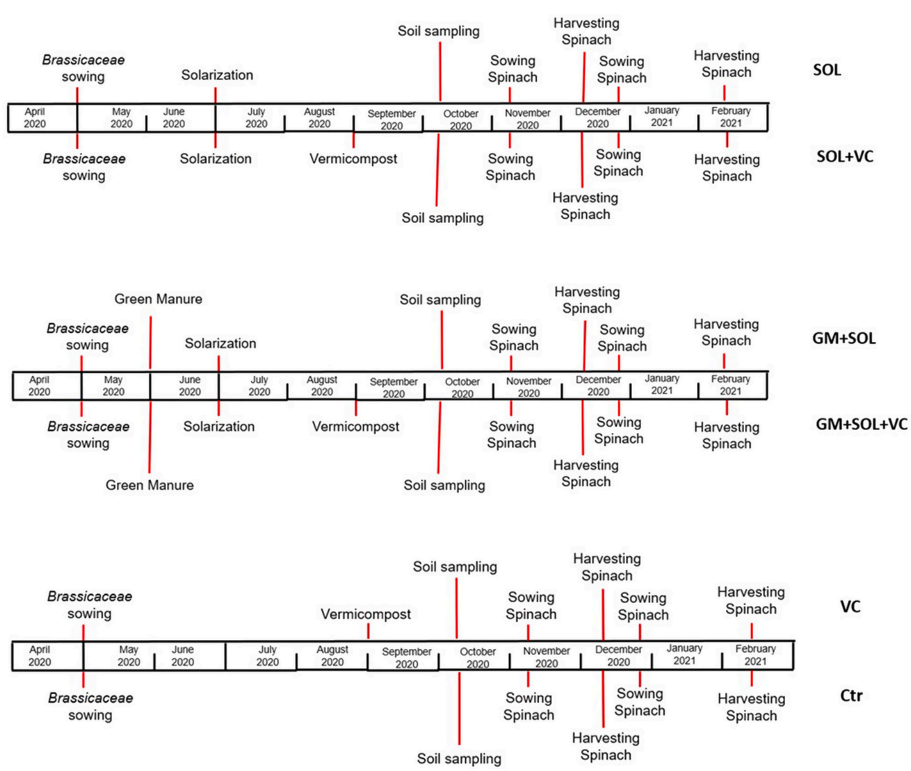

Fig. 1. Graphical illustration of the experimental design for 5 treatments and control.
Note: Ctr = Control; SOL=Solarization; GM = Green Manure; VC=Vermicompost. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

item has outer loadings above 0.7 and when each Average Variance Extracted (AVE) of the construct is equal to 0.5 or higher. The AVE measures the variance of the indicators explained by the construct. Then, the sensitivity analysis was conducted to depict the value production of spinach under different soil treatments at changing the price of vermicompost. All statistical analyses were conducted using Stata 16 (Stata Corp LP, College Station, TX, USA).

3. Results

3.1. Exploratory Factor Analysis

An explanatory factor analysis was conducted on the soil parameters to reduce them. The EFA identified five main latent constructs, as shown by the factor loadings in columns two to six of Table 3. The last column summarizes the fraction of information from each soil parameter not taken into account by the five factors (uniqueness). The first two latent constructs (Factor 1 and Factor 2) were positively correlated with nutrients. Phosphorus, sodium, and potassium were strictly associated with each other in a unique dimension named "Nutrients_1", while nitrogen, sulfur, and magnesium defined the "Nutrients_2" dimension. Similarly, Factor 3 and Factor 4 defined the "Fungal Biodiversity" and "Bacterial Biodiversity" dimensions, respectively, while the positive correlation between biochemical soil parameters defined Factor 5, which is the fifth dimension named "Biochemical Soil Quality."

3.2. Effects of vermicompost on spinach yield and soil characteristics

Table 4 presents the mean values and their standard errors for spinach yield and soil characteristics after all soil treatments considered in the experiment. ANOVA and Tukey post-hoc tests revealed significant differences among the mean values of treatments for both yield and soil characteristics. For spinach yield, the highest production value was observed when the soil was treated with solarization (SOL) and vermicompost (VC) (1.787 ± 0.036), corresponding to an increase of the yield of 15 % comparing to control plot. The lowest mean value of yield was related to the VC treatment alone (1.364 ± 0.036), −12 % comparing to control plot.

As for the soil characteristics parameters, the factor scores represent standardized values of the original variables and have mean of 0 and a standard deviation of 1. In this case, a difference of 1 unit in factor score represents a difference of 1 standard deviation. The combination of solarization and vermicompost (SOL+VC) also showed the highest values for the biochemical parameters of the soil (1.019 ± 0.204) as well as for the organic carbon (0.677 ± 0.255). In terms of nutrients, the combination of green manure, vermicompost, and solarization (GM+SOL+VC) showed the highest values for both Nutrients_1 (1.208 ± 0.196) and Nutrients_2 (0.897 ± 0.252), while the highest fungal biodiversity was observed after solarization (0.936 ± 0.248). No treatments increased the bacteria biodiversity, so the control (Ctr) had the highest value (0.738 ± 0.256).

3.3. PLS-SEM output

Having observed the effect of the treatments on yields and different soil characteristics (biochemical, fungal, and bacterial biodiversity, nutrients), the next step involves understanding the mechanisms of action of the treatments on yields. Specifically, it is necessary to identify which soil parameters are affected by the different treatments and how soil parameters change may contribute to improving yields. To this end, a PLS-SEM model is being developed that is suitable for the empirical verification of hypotheses regarding functional relationships. This model will allow us to determine whether and how modifications to soil parameters following the treatments have a direct role in influencing yields, and thus to establish the specific mechanisms of action that the different treatments follow in affecting yields.

3.3.1. The measurement model output

The measurement model output is illustrated in Table 5. All constructs were *ex ante* defined according to the results of the EFA. All standardized loadings, meaning the correlations between the latent constructs and each soil parameter (indicator reliability), are greater than |0.4|. The results confirm that the "Nutrients_1" dimension is strongly correlated with three nutrients: phosphorus (0.794), sodium (0.860), and potassium (0.898), while nitrogen (0.572), sulfur (0.746), and magnesium (0.959) define the "Nutrients_2" dimension. On the other hand, "Fungal biodiversity" is primarily characterized by the fungal Shannon (0.991) and fungal Simpson (0.988) indices, and "Bacterial biodiversity" is represented by bacterial Shannon (0.993) and bacterial Simpson indices (0.986). Finally, "Biochemical soil quality" is well represented by beta-glucosidase (0.668), alkaline phosphatase (0.786), and acid phosphatase (0.850).

To assess the validity of the measurement model (Venturini and Mehmetoglu, 2019), the internal consistency was also evaluated. The most popular indexes of internal consistency, such as Cronbach's alpha, Dillon-Goldstein's rho (DG), and rho A coefficients, are above the threshold value of 0.6. The average variance extracted (AVE) scores were close to the threshold of 0.50, indicating convergent validity, while the results of the Fornell-Larcker criterion showed that none of the squared correlations had a higher value than the AVE scores, indicating that the discriminant validity of the constructs was established.

Table 3
Exploratory Factor Analysis (EFA) using orthogonal (Varimax) rotation: factor loadings. EFA results on the thirteen soil parameters. Five main soil characteristics were successfully extracted from the overall parameters. Factor loadings indicate the correlation between the attribute and the latent construct. Uniqueness shows the proportion of variance unaccounted for by the latent dimensions.

Soil parameters	Factor1	Factor2	Factor3	Factor4	Factor5	Uniq.
	Nutrients_1	Nutrients_2	Fungal Biodiversity	Bacterial Biodiversity	Biochemical Soil Quality	
β-glucosidase					0.673	0.175
Alkaline phosphatase					0.821	0.276
Acid phosphatase					0.708	0.250
Total nitrogen		0.699				0.461
Assimilable phosphorus	0.810					0.168
Calcium		0.842				0.209
Magnesium		0.735				0.212
Sodium	0.873					0.188
Potassium	0.737					0.143
Bacterial Shannon index				0.984		0.019
Bacterial Simpson index				0.974		0.035
Fungal Shannon index			0.946			0.038
Fungal Simpson index			0.965			0.037

Note: Loadings greater than |0.4| are shown and used for interpretation.

Table 4
Mean and standard error of five soil treatments on Spinach yield and soil characteristics.

Treatments	Yield (kg/m^2)	Bioc_qual	Nut_1	Nut_2	Fun_Biod	Bat_Biod	Org_Carb
Ctr	1.55^{b}	−.781^{a}	−.901^{b}	−.208^{ab}	−.300^{a}	**.738^{d}**	−.327^{bc}
St.Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*
SOL	1.575^{b}	−.435^{a}	−.917^{b}	.103^{a}	**.936^{c}**	−.613^{ab}	−.907^{c}
St.Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*
SOL+VC	**1.787^{a}**	**1.019^{c}**	.175^{a}	−.893^{b}	.531^{bc}	−.001^{abc}	**.677^{a}**
St.Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*
GM+SOL	1.729^{a}	−.857^{a}	.484^{a}	.227^{ac}	−.457^{a}	−.666^{a}	−.013^{ab}
St.Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*
GM+SOL+VC	1.708^{a}	.375^{b}	**1.208**	**.897^{c}**	−.609^{a}	.078^{bcd}	.112^{ab}
St. Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*
VC	1.364	.678^{bc}	−.050^{a}	−.126^{a}	−.101^{ab}	.465^{cd}	.458^{a}
St.Err	*.036*	*.204*	*.196*	*.252*	*.248*	*.256*	*.255*

Note: Ctr=Control; SOL=Solarization; GM=Green Manure; VC=Vermicompost; Nut_1: plant nutrients; Nut_2: plant nutrients; Fun_bio: fungal biodiversity; Bat_bio: bacterial biodiversity; Bioc_qual: biochemical quality of soil; Org_Carb: organic carbon. Statistical differences were tested using ANOVA and Tukey's honestly significant difference (HSD) post hoc test. Different letters stand for statistically significant differences among treatments at $p < 0.05$. St. Err = standard error. Highest margin per Spinach yield and soil characteristics were shown in bold.

Table 5
Factor loadings, Cronbach's α, rho A and Dillon-Goldstein of the measurement model.

	NUT_1	NUT_2	FUN_BIO	BAC_BIO	BIOC_QUAL	ORG_CARB	SOL	SOL + VC	GM + SOL	GM + SOL + VC	VC	Spinach_Yield
Phosphorus	0.794											
Sodium	0.860											
Potassium	0.898											
Nitrogen		0.572										
Soccer		0.746										
Magnesium		0.959										
Shannon_F			0.991									
Simpson_F			0.988									
Shannon_B				0.993								
Simpson_B				0.986								
Beta-glucosidase					0.668							
Alkaline phosphatase					0.786							
Acid phosphatase					0.850							
ORG_CARB						1.000						
SOL							1.000					
SOL+VC								1.000				
GM+SOL									1.000			
GM+SOL+VC										1.000		
VC											1.000	
Spinach Yield												1.000
Cronbach	0.812	0.717	0.978	0.980	0.667	1.000	1.000	1.000	1.000	1.000	1.000	1.000
DG	0.888	0.813	0.989	0.990	0.814	1.000	1.000	1.000	1.000	1.000	1.000	1.000
rho_A	0.843	1.344	0.997	1.079	0.711	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Note: Nut_1: plant nutrients; NUT_2: plant nutrients; FUN_BIO: fungal biodiversity; BAC_BIO: bacterial biodiversity; BIOC_QUAL: biochemical quality of soil; ORG_CARB: organic carbon. SOL=Solarization; GM=Green Manure; VC=Vermicompost.

3.3.2. *The structural model output*

The direct effects of the structural model are illustrated in Fig. 2. Each oval corresponds to a latent construct, and the arrows represent the relationships among the constructs. All soil treatments are represented by a rectangle. The arrows connecting the rectangle and each soil characteristic represent the relationships between the soil treatments and soil characteristics. Results of the direct effects of the structural model are revealed in Table 6. Our results showed that nutrients have a positive effect on the observed yield (NUT_1: +0.506; NUT_2: 0.362) while the Biochemical soil quality (including Beta-glucosidase, Alkaline phosphatase, Acid phosphatase) and the Organic Carbon seems impacting negatively the yield (−0.326; −0.187 respectively). No statistically significant relationships have been found for both Fungal and Bacterial biodiversity. Vermicompost combined with solarization (SOL+VC treatment) has been confirmed to have a positive effect on i) nutrients (NUT_1: 0.207; p=0.010), ii) fungal biodiversity (FUN_BIO: 0.281; p=0.033), iii) biochemical quality of soil (BIOC_QUAL: 0.676; p<0.001) and iv) organic carbon (ORG_CARB: 0.377; p=0.007).

Note: Nut_1: plant nutrients; NUT_2: plant nutrients; FUN_BIO: fungal biodiversity; BAC_BIO: bacterial biodiversity; BIOC_QUAL: biochemical quality of soil; ORG_CARB: organic carbon; SOL=Solarization; SOL=Solarization; GM=Green Manure; VC=Vermicompost.

3.3.3. *Farmer's economic profitability*

The cost of vermicompost-treated soil is derived from the indicative price of the vermicompost considered in this study, which is equal to 0.40 euro per kilo, plus the costs for spreading, i.e. 250 euro/ha. Given that the amount of vermicompost used in the treatments is 0.400 kg per square meter of surface, we can calculate the cost of vermicompost per square meter by adding the price of vermicompost per square meter (0.16 euros) to the cost of spreading each square meter (0.02 euros), for a total cost of 0.18 euros/m^2. Table 7 shows the economic profitability of each soil treatment included in the experimental design.

The SOL+VC treatment shows the highest economic benefit per m^2 (2.52 euros), followed by vermicompost treatment (2.41 euros/m^2). The lowest economic benefit is achieved by combining green manure, solarization, and vermicompost (1.85 euros/m^2). Therefore, if the spreading costs are considered fixed, the economic benefits for farmers

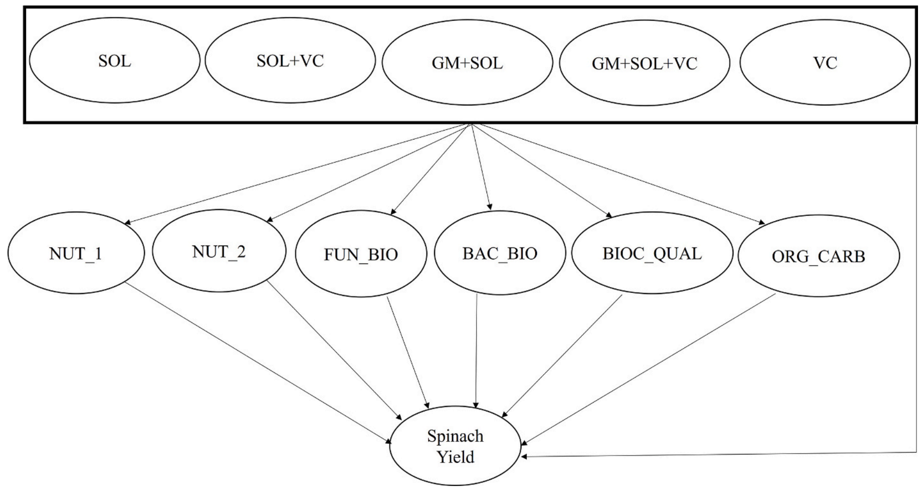

Fig. 2. Graphical representation of the direct effects.

Table 6
Direct effects of the structural model.

Independent variable	Dependent variable						
	NUT_1	NUT_2	FUN_BIO	BAC_BIO	BIOC_QUAL	ORG_CARB	YIELD
SOL	−0.215**	0.429***	0.485***	−0.558***	0.198*	−0.218	0.078
SOL+VC	0.207*	0.141	0.281**	−0.260*	0.676***	0.377**	0.642***
GM+SOL	0.435***	0.462***	−0.072	−0.459***	0.086	0.118	−0.007
GM+SOL+VC	0.815***	0.801***	−0.143	−0.237*	0.559***	0.165	−0.204
VC	0.210**	0.291**	0.040	−0.084	0.603***	0.294**	−0.338**
NUT_1							0.506**
NUT_2							0.362**
FUN_BIO							−0.149
BAC_BIO							−0.032
BIOC_QUAL							−0.326**
ORG_CARB							−0.187**

Note: NUT_1: plant nutrients; NUT_2: plant nutrients; FUN_BIO: fungal biodiversity; BAC_BIO: bacterial biodiversity; BIOC_QUAL: biochemical quality of soil; ORG_CARB: organic carbon; SOL=Solarization; GM=Green Manure, VC=Vermicompost.

Table 7
Economic profitability of soil treatment.

Soil Treatment	Cost of treatment (€/m^2)	Yield of spinach (kg/m^2)	Price of spinach (€/kg)	Gross Production Value (€/m^2)	Economic Benefit (GPV-Cost of treatment)
SOL	0.70	1.58	1.90	2.99	2.29
SOL+VC	0.88	1.79	1.90	3.40	2.52
GM+SOL	1.22	1.73	1.90	3.29	2.07
GM+SOL+VC	1.40	1.71	1.90	3.25	1.85
VC	0.18	1.37	1.90	2.59	2.41

depend solely on the market price of vermicompost. The next step is to analyze the maximum price at which vermicompost (VC) would still be a viable solution for spinach farmers.

Fig. 3 presents the results of a sensitivity analysis which shows that the return of spinach production decreases as the cost of VC per square meter increases, holding the cost of other treatments constant. Specifically, the VC remains a viable solution for spinach farmers with a cost equal to or lower than 0.38 euro per square meter (0.84 euro per kg) when the soil is treated with both VC and solarization; beyond 0.38 euros per square meter, the use of VC becomes less attractive to farmers. Soil treated only with VC yields a lower production value compared to soil treated with VC and solarization, lowering the farmer's willingness to pay for vermicompost by 0.10 euros, demonstrating economic convenience for a cost of VC less than 0.28 euro per square meter (0.62 euros per kg). On the other hand, the combination of VC with solarization and green manure produces the lowest value of production for all levels of price of VC.

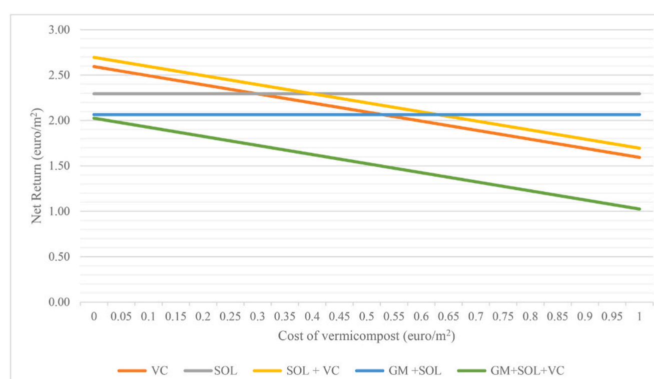

Fig. 3. Net return on spinach production (euro/m^2) in relation to changing costs (euro/m^2) of vermicompost.

4. Discussion

Our findings showed that vermicompost reduced spinach yield, but the yield increased when soil was treated with vermicompost after solarization. This result aligns with several previous studies that found lower spinach yield with soil treated only with vermicompost compared to other treatments [14,39]. For example, Salma and Hossain (2021) reported a higher spinach yield with soil treated with neem cake followed by vermicompost, while Ansari [14] found a significant increase in spinach yield with soil treated with vermiwash. However, a recent meta-analysis by Blouin and colleagues [40] stated that vermicompost has a positive effect on plant growth. Specifically, Xu and Mou [41] found that spinach plants grew better after vermicompost treatment. Our results showed that the combination of vermicompost and solarization had a positive effect on soil characteristics such as nutrients, fungal biodiversity, and biochemical quality. The positive impact of vermicompost on soil fertility is well-documented for several crops, e.g. pea cultivation [42] and cucumber [15]. A more in-depth analysis of the effects of vermicompost on soil characteristics is provided by Lazcano and Dominguez [43], who reported an increase in soil nutrients and organic carbon after vermicompost treatment. They also found higher enzyme activity in soil treated with vermicompost and increased microorganism growth. In contrast to Lazcano and Dominguez [43], who found a significant effect of vermicompost on bacterial growth and no significant effect on fungal growth, our findings showed higher fungal biodiversity in soil treated with vermicompost after solarization and lower bacterial biodiversity. Moreover, the economic profitability due to the use of vermicompost is consistent with a few recent studies that have examined the economic performance of vermicompost in the cultivation of broccoli ([17] and strawberries [18]. However, unlike our finding, Tascı and Kuzucu [17] demonstrated that combining vermicompost with green manure enhances the profitability of the farm. The current study goes beyond simply assessing the impact of vermicompost on spinach cultivation and soil quality. It also shows a real case of multiple advantages of industrial symbiosis in the agri-food sectors, affirming insights by Roy and colleagues [44]. This symbiotic network not only creates economic value for upstream actors such as millers, biogas producers, and mozzarella manufacturers by i) introducing a new marketable product—vermicompost, and ii) reducing waste management costs, but also offers economic gains for downstream actors, farmers. Specifically, when properly employed, this vermicompost can improve the productivity of spinach. Importantly, the availability of these byproducts and their resultant profitability is intrinsically linked to the symbiotic network. Therefore, the economic benefits observed provide empirical evidence supporting the sustainability of this industrial symbiosis, making it a win-win proposition for the sector.

Indeed, the strategic role of industrial symbiosis in agriculture has recently been emphasized by Hamam and colleagues [11]. The current study's findings are very encouraging because they show, in relation to the case study, the economic benefit of using a product that is the result of industrial symbiosis. Considering what Neves and colleagues [8] stated, namely that the economic component is the most important driver of the implementation of the CBE, the adoption of this amendment is facilitated by the economic benefit that the farmer can reap after its use. As a result, the use of vermicompost among organic spinach farmers does not require policymaker incentives at least for the time being; rather, it requires a commitment from agricultural advisory services offering advice to farmers and emphasizing its economic and environmental sustainability. The current study has proved that industrial symbiosis can effectively represent the right tool for the agricultural sector's implementation of the circular bio-economy in order to valorize agricultural by-products by creating economic value. The study's findings contribute to the existing literature through an empirical examination of the economic viability of implementing industrial symbiosis in a specific region of Southern Italy. Furthermore, this work enriches the scientific literature with information about the direct and indirect effects that this specific vermicompost (made from olive mill wastewater, milk whey, and buffalo slurry) can have on greenhouse-grown spinach and soil quality. Additionally, it provides insights into the economic feasibility of its use compared to other farming practices, thus enriching the literature discussion on the economic viability of using vermicompost. Ultimately, the research contributes to the ongoing discourse on the imperatives of aligning economic incentives with environmental sustainability, presenting a compelling case for an integrated approach that benefits multiple stakeholders while minimizing environmental impact.

4.1. Practical implications of the study

The study findings offer relevant practical implications for all stakeholders involved, demonstrating the viability of establishing industrial symbiosis among farmers, millers, biogas producers, and mozzarella manufacturers, built on the use of vermicompost. In this context, targeted technical assistance is essential for all parties, particularly farmers, to understand the technical aspects related to vermicompost treatment and its efficacious application in greenhouse cultivation. On a broader scale, the research highlights the effectiveness of collaborative efforts, when combined with the utilization of biogas facilities, in optimizing the use of agricultural byproducts, thereby facilitating the shift towards a circular economy in the agricultural sector. These findings can inform guidelines that encourage the adoption of sustainable agricultural practices, thus potentially incentivizing the sector transition towards a circular bio-economy. Importantly, the study emphasizes the economic and environmental sustainability that is inherent in the industrial symbiosis between agri-food sectors, thereby strengthening the case for its broader implementation. Thus, our results elucidate a win-win strategy that enhances productivity while promoting sustainable agricultural practices, thereby offering actionable insights for both operators and policymakers in the agri-food sectors.

5. Conclusions

Industrial symbiosis is widely recognized as an effective tool for implementing the circular bio-economy in modern times. This study examined the potential for developing a circular bio-economy process in a region of Southern Italy that is known for its agricultural and livestock industries. An analysis was conducted on the industrial symbiosis between anaerobic digestion plants, mills, livestock farms, and fresh-cut vegetable farms, with a focus on the economic benefits (in terms of crop yield) for fresh spinach producers. Vermicompost, a soil enhancer made from a digestate produced from the anaerobic digestion of buffalo slurry, olive mill wastewater, and milk whey, was used in the evaluation. A Partial Least Square Structural Equation Modeling (PLS-SEM) approach was applied to analyze effects of vermicompost on spinach yield and soil characteristics. The results of the study indicated that vermicompost alone decreases spinach yield. However, combining vermicompost with solarization increases yield and improves soil quality in terms of nutrients, biochemical and microbiological activities. Therefore, this result suggests the possibility of replacing green manure in greenhouse spinach cultivation with vermicompost while reducing the costs associated with spinach cultivation. This study is not without limitations, including its focus on only one crop (i.e spinach) and one production system (i.e.organic). Additional limitations can be found in the fact that it analyzes a greenhouse located in a specific area of Southern Italy, collecting data for a single agricultural year. Based on these results, further studies could explore the effects of vermicompost on spinach yield and soil quality over multiple years. Moreover, future research should investigate the potential effects of vermicompost on the qualitative characteristics of spinach, such as the content of leaf nitrate and/or minerals (e.g., iron) and vitamins (e.g., vitamin A and C) as well.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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