

Article

Enhancing Water Use Efficiency and Carbon Profitability Through the Long-Term Impact of Sustainable Farming Systems

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Abstract: This study aims to enhance water use efficiency, maximize productivity, and minimize environmental impact through the implementation of sustainable agricultural systems using drip irrigation systems. It investigates the effects of biodynamic farming compared to those of organic and conventional methods over a six-year period and focuses on soil properties, water use efficiency, crop yield, and environmental and economic perspectives. Using a biodynamic farming system resulted in an average increase in water use efficiency of 1.96 and 10.67% for maize and 3.62 and 10.68% for faba bean and an increase in maize yield of 1.68 and 0.99%, while the faba bean yield reached 3.25 and 1.57% compared to the organic and conventional farming systems, respectively. The biodynamic system sequestered the highest average soil carbon of 6.16 tons/ha (which is equivalent to 22.45 tons/ha of CO₂ emissions), representing a 13% increase compared to the organic system. Additionally, the biodynamic system yielded an increase in total net profit of 5.70 and 21.66% for the maize crop and 6.72 and 22.19% for the faba bean crop compared to the organic and conventional farming systems, respectively. The farming system significantly influenced the soil carbon sequestration and organic carbon.

Keywords: organic farming system; biodynamic farming system; conventional farming system; soil carbon sequestration; water use efficiency; crop yield; cost analysis



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1. Introduction

Climate change is considered to be one of the most critical issues globally, with rising concentrations of carbon dioxide (CO₂) and other greenhouse gases (GHGs) in the atmosphere leading to global warming. Sustainable agriculture is an ecologically friendly farming approach that fosters positive economic and environmental outcomes. Its aim is to produce healthy food without causing adverse effects on the natural environment. An integrated farming system is a sustainable agricultural system that integrates livestock, crop production, crop farming, and other mutually beneficial systems and is based on the concept of zero waste. Changes in land use influence greenhouse gas emissions in the agriculture sector, particularly CO₂, which is estimated to account for 20% of the total greenhouse gas emissions. Climate change impacts crop productivity directly and indirectly [1]. Globally, soil carbon sequestration represents the primary mechanism for significant mitigation potential within the agricultural sector, contributing an estimated 90% to the technically feasible potential [2].

Organic farming depends on enhancing soil structure through the use of organic fertilizer (compost) as a substitute for inorganic fertilizers. Additionally, animal manure is utilized to provide a nitrogen source for plants. The addition of compost decreases nitrogen and phosphorus runoff and their concentration in waste, thereby increasing water reusability [3]. The production technology for biofertilizers is relatively simple, and installation costs are significantly lower compared to those of chemical fertilizers. Using biofertilizers (bacterial and fungal) in the soil promotes growth by increasing the supply or availability of primary nutrients for plant growth, like hormones, vitamins, and amino acids. Reducing the use of chemical fertilizer is essential to minimize environmental risks and plays a crucial role in preserving soil fertility [4]. Biofertilizers are crucial components of organic farming and play a critical role in maintaining long-term soil fertility and sustainability. Moreover, biofertilizers as a partial replacement for chemical fertilizers reduce the quantity and cost of chemical fertilizers; thus, they prevent the environmental pollution that results from the extensive application of chemical fertilizers and help farms to achieve sustainability [5]. The continuous use of organic and inorganic fertilizers influences the soil's physical and chemical properties. Over a period of 24 years, plots treated with manure resulted in the highest soil organic carbon (SOC) and total nitrogen (TN). However, the application of commercial fertilizers led to a decrease in soil pH over time, albeit with higher yields compared to the use of manure fertilizer [6]. Organic manures enhance the soil fertility and crop yield by rendering unviable sources of elemental nitrogen-bound phosphate and decomposed plant residues into an available form that allows the plant to absorb the nutrients [7]. Organic farming is regarded as one of the most effective methods for mitigating water quality degradation and reducing food toxicity. In this farming system, crops are cultivated without the use of chemicals. In addition, it maintains biodiversity and reduces the anthropogenic footprint on soil, air, water, and wildlife, especially in farming communities. Fields managed organically for extended periods exhibit reduced pest populations; this reduction is attributable to enhanced biodiversity, increased trophic interactions, and alterations in plant metabolites [8].

Biodynamic farming is a regenerative approach to organic agriculture that emphasizes self-sustainability. The biodynamic standard does not allow any added hormones and avoids synthetic pesticides and fertilizers. Instead, manure is buried in cow horns and strengthened throughout the wintertime and is used as a homeopathic fertilizer; this method of fertilizing creates high-quality and purely functional active ingredients. The effect of biodynamic preparations of horn manure and silica (BP) on soil physical and biological properties was studied. To comprehend the potential transformation processes, soil samples were collected every six months over a period of three years. All the vineyards were managed organically, but two plots for were considered for treatment with BD (BD+) and without BP as a control (BD-). The experimental findings suggest that water availability may have increased through the application of BD. The pH exhibited significantly higher values in the plots treated with BP+ (7.85) compared to those without (BP-), which recorded 7.69. Low rates of microbial basal respiration may indicate increased soil carbon storage. The BP application showed a positive effect on some soil physical properties, necessitating further investigation across various seasons and correlation with microbial activity [9]. As an environmental and ethical approach to farming, a DOK experiment (bioDynamic, bioOrganic, Konventionell (traditional German)) was conducted in 1978 in Therwil. After 42 years, the SOC contents increased in BIODYN 1.4 and also, to a lesser extent, in BIORG 1.4. CONFYM showed 1.4 stable SOC contents, while the manure-enriched systems lost 0.7 animal units and CONMIN SOC. The highest SOC loss was in NOFERT. Improving soil biological quality under organic management, especially biodynamic management, underscores the intimate connection between soil biology and the change in SOC. Recycling manure at a rate of 1.4 animal units per hectare facilitates the maintenance of SOC levels, while composting practiced in BIODYN 1.4 aids in increasing SOC levels and enhancing biological soil quality [10].

From the literature review above, it is evident that numerous studies have explored organic and conventional farming systems, while relatively few have addressed the impact of biodynamic farming systems. The limitations of producing organic or biodynamic foods are that they are more expensive and have a lower crop yield than conventional foods; the use of chemical fertilizers and pesticides is more attractive. Through this study, the authors aim to investigate the effects of implementing a sustainable biodynamic system on soil properties, water saving, crop productivity, and environmental–economic considerations in comparison with other systems over a six-year period. So, the objectives of the current study are to:

- Investigate the long-term effects of farming systems (biodynamic, organic, and conventional) on soil properties and soil carbon sequestration.
- Enhance water use efficiency and crop yield through the implementation of various farming systems using a drip irrigation system.
- Assess the utilization of different farming systems from both economic and environmental perspectives.

This work innovatively introduces a six-year consecutive agricultural pilot system under drip irrigation, enabling precise validation of the impact of different sustainable farming systems on each of the following parameters: soil, water, crops, and environmental and economic viewpoint; these are to be validated with precision in order to achieve practical and applicable results. Research methodology and measurements were used to measure the soil properties and water use efficiency and to mitigate environmental impact. Statistical analysis was used to compare the effects of different farming systems during different growing seasons. The validation of the application of a farming system based on measurements and results will enable its adoption in a sustainable, eco-friendly manner.

2. Materials and Methods

The present study was conducted at SEKEM farm (30.421 Latitude and 31.635 Longitude), Belbeis, Al-Sharqia Governorate, Egypt, from 2016/2017 to 2021/2022.

2.1. Experimental Setup

The experiments were executed at about 1.5 fed (0.63 ha), consisting of 27 plots with an approximate area of 240 m² (20 × 12 m) for each plot, and 3 crops were grown per agricultural season.

2.1.1. The Experimental Soil

Soil samples were collected at a depth of 30 cm using a soil auger with a diameter of 25 mm. The collected samples were thoroughly mixed to ensure homogeneity, and any impurities were subsequently removed. Afterwards, the samples were air-dried and sieved through a 2 mm mesh sieve before analysis and kept in sealed containers at 4 °C before the analysis [11]. The experiment was conducted on sandy soil consisting of 88% sand, 9.5% silt, and 2.5% clay.

2.1.2. Drip Irrigation System

Precision irrigation aids farmers in mitigating climate risks; a surface drip irrigation was system employed in this study. The drip irrigation system consisted of a control head (centrifugal pump, pressure regulator, pressure gauges, flow meter, and filtration unit) and PVC main, sub-main, secondary, and manifold lines with 160, 110 and 90, and 63 and 40 mm diameters, respectively, as illustrated in Figure 1. The emitters (GR) utilized in the study were installed in lateral lines of polyethylene (PE) with a diameter of 16 mm; the distance between emitters was 30 cm, and each emitter had a discharge of 4 L/h. The network was planned according to the nature of the land and the experimental conditions to fit 27 experimental plots. The manifold line was equipped with a valve, pressure gauges, and a flow meter, which was located at the beginning of each plot to control and determine the amount of water for each plot. Additionally, the network was equipped with a venturi

meter device to add fertilization during irrigation and to ensure that the application of fertilizer in each plot was in accordance with the recommendations of the Egyptian Ministry of Agriculture.

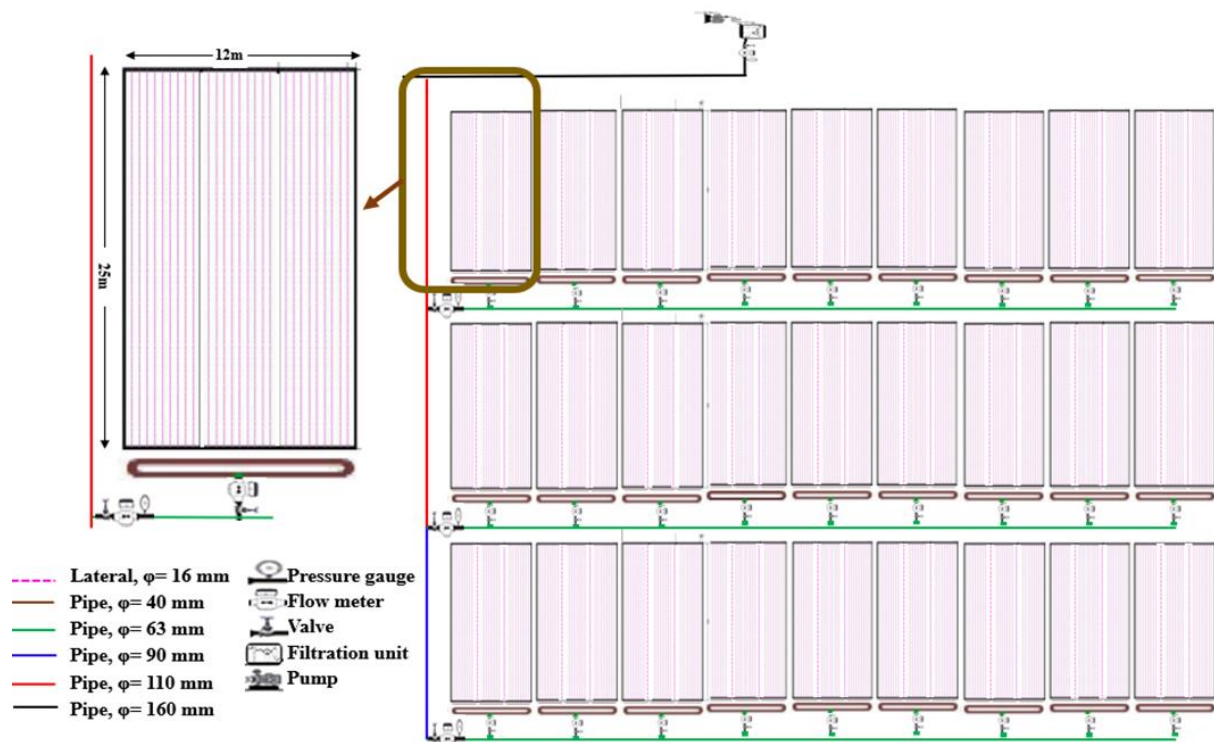


Figure 1. Layout of the used drip irrigation system.

2.1.3. The Cultivated Crops

Different crops were cultivated in an experimental area to assess the long-term effects of farming systems over six years, with three crops planted each agricultural season. During the winter season, wheat, faba bean, and tomato were planted, while in the summer season maize, soybean and potato were grown using the drip irrigation system. However, this study focused exclusively on two crops, faba bean and maize, to elucidate the impact of farming systems as an indicator for other crops under Egyptian conditions. According to [12], the total harvested area of faba bean (*Vicia faba* L.) was 26,382 ha, yielding 3.9819 tons/ha (planted from October to April.), while the total harvested area of maize (*Zea mays* L.) was 1,027,057 ha, with a yield of 7.3024 tons/ha (planted from May to September). All the agronomic techniques, agricultural practices, and fertilizer rates were implemented in accordance with the recommendations of the Agriculture Research Center, Ministry of Agriculture, Egypt.

2.2. Experimental Procedure

The experiment was designed in a randomized block with three field replicates for each of the three crops grown each season using three farming systems, resulting in twenty-seven experimental plots, as shown in Figure 2. Different crops and farming systems were randomized in the experimental plots. Data collection involved taking readings three times (replicates) during each month of the growing season across three consecutive agricultural seasons.

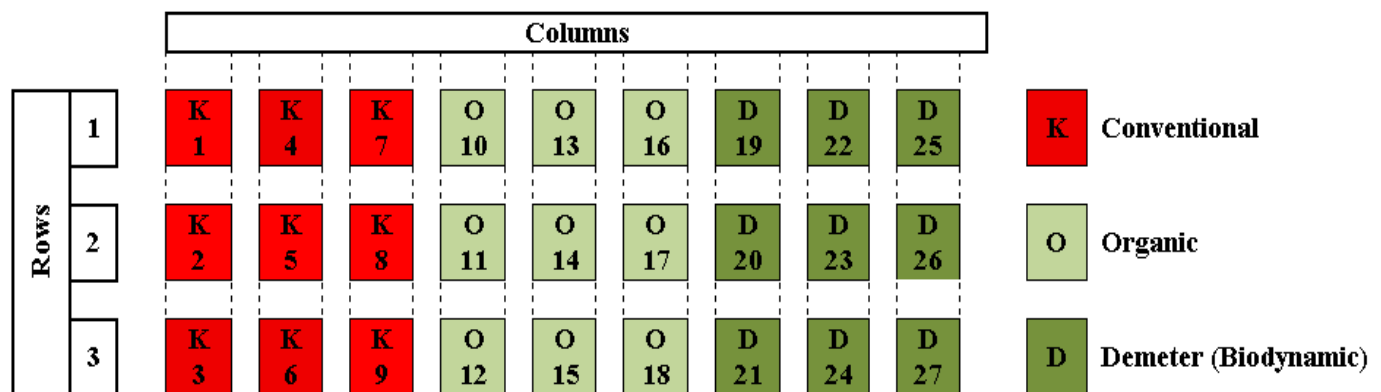


Figure 2. Field setup of the experiment.

2.2.1. Experimental Conditions

The following experimental treatments were conducted through six consecutive growing seasons, as illustrated in Figure 3:

- Three types of farming systems were studied: biodynamic, organic, and conventional.
- Two crops were cultivated: faba bean and maize.

Compost was incorporated into the soil at a rate of 24 tons/ha during soil preparation in the organic and biodynamic farming systems. The analysis of the used compost was as follows: the weight of 1 m³ was 650 kg, 7.42 pH, 7.77 dS/m EC, 35.91% organic matter (OM), 20.83% organic carbon (OC), 16:1 C/N ratio, 1.27% total nitrogen (N), 1.05% total phosphorous (P), 0.80% total potassium (K), and 64.09% ash without weed seeds.

Herobiofert was used as a fertilizer in the organic and biodynamic farming systems, and this compound was manufactured locally by SEKEM farm from various ingredients, such as biogas, bacteria, compost tea, and some additions of humic acid and fulvic acid with a certain percentage of each element. It was used at the recommended dose of 300 L/fed (714.29 L/ha) divided four times. The biofertilizer compound's chemical analysis was 0.73% total nitrogen, 0.19% NH₄, 0.45% NO₃, 1.20% total phosphorous, 1.92% total potassium, and 2.30% total amino acid.

Regarding the use of a biodynamic farming system, the same practices were implemented in the organic fertilization system, in addition to the use of additional treatments like adding horn manure in the amount of 150 g/fed (357.14 g/ha) immediately after planting using a sprayer. The silica was added in the amount of 2 g/fed (4.76 g/ha) 3 times.

For the conventional plots, mineral fertilizers were utilized, including ammonium nitrate (34N-0P-0K), superphosphate 15.5 P, calcium nitrate 15 Ca, and potassium 48 K.

Nitrate fertilizer and organic fertilizer (Herobiofert) were applied through fertigation according to the recommended doses.

2.2.2. Measurements and Determinations

To evaluate the impact of the farming systems, the following indicators were considered:

- Soil physical and chemical properties

To investigate the influence of different farming systems on soil properties, soil samples were collected throughout the 6-year growing seasons and the soil physical and chemical characteristics were estimated according to the standard methods of [13,14]. Soil bulk density, water-holding capacity (WHC), pH, EC, soil organic matter (SOM) and soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were determined. The soil carbon sequestration (ton/ha) under the influence of different farming applications in the farmland was calculated from the variations in the total amount of soil carbon between the treatments.

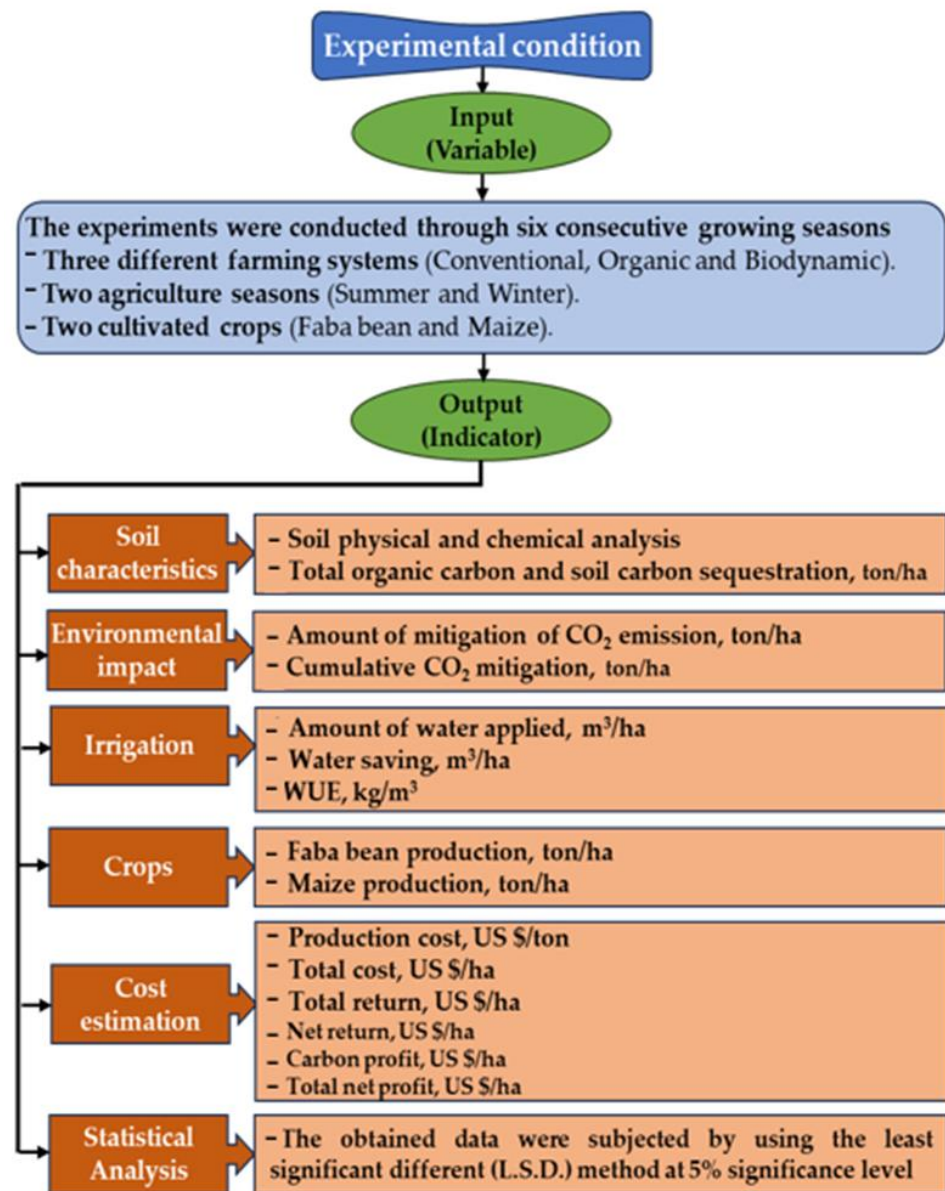


Figure 3. Schematic diagram of experimental conditions.

■ Crop yield

The yield of the maize and faba bean crops was determined (ton/ha) to study the effect of the different farming systems. To calculate the yield, an area of 1 m² (1 m × 1 m) was selected within different experimental plots; the number of grains or seeds in at least ten random heads was counted; and the average yield (g) per head (m²) was calculated. Then, the actual yield from the harvested area was converted to ton/ha.

■ Amount of water applied

The actual amount of water applied under different farming systems using the drip irrigation system was calculated using the equation given in [15]:

$$IR_a = \{[(\theta_{FC} - \theta_v) \times d] + Lf\} / E_s \quad (1)$$

where IR_a: total actual water applied (mm); θ_{FC}: soil moisture content at field capacity (%); θ_v: soil moisture content before irrigation (%); d: soil depth (mm); Lf: leaching factor, 20% for the drip irrigation system according to [16]; and E_s: drip irrigation system efficiency (85%). The soil moisture content was measured using an electronic sensor, Delta-T-Devices,

profile Probe PR2, England. The amount of irrigation water applied for each treatment during growing seasons was measured using a calibrated flow meter (m^3).

- Water use efficiency

Water use efficiency (WUE, kg/m^3) was used to evaluate the various treatments as it can be expressed as the weight of crop yield per unit of consumed water, according to [17]:

$$\text{WUE} = (\text{Yield} / \text{Amount of water applied}) \quad (2)$$

- Economic estimation

An economic analysis was conducted to ascertain the optimum economic conditions using the different farming systems, as follows:

The total cost (TC, USD/ha) was calculated considering the costs of all the farming operations for the soil preparation, fertilization, cultivation cost, pesticide cost, labor cost, energy consumption, and total irrigation cost. It was computed using:

$$\text{TC} = \text{Fixed costs} + \text{Variable costs} \quad (3)$$

Total return (TR, USD/ha) was calculated with the following equation:

$$\text{TR} = \text{Crop price (US \$ /ton)} \times \text{Yield (ton/ha)} \quad (4)$$

However, there was an increase in the sale price of the final organic and biological products of 20 and 25%, respectively, compared to the conventional product, according to [18]. In the current study, the estimation was performed at the same rate to illustrate the impact of soil carbon sequestration and its relationship to yield in economic terms.

Net return (NR, USD/ha) was calculated with:

$$\text{NR} = \text{TR} - \text{TC} \quad (5)$$

The production cost (PC, USD/ton) was estimated using the following equation:

$$\text{PC} = \text{Total cost} / \text{Crop yield} \quad (6)$$

The profit analysis for mitigation of CO_2 emissions (PCO_2 , USD/ha) was calculated using the following equation:

$$\text{PCO}_2 = \text{Am}_{\text{CO}_2} \times \text{Mp} \quad (7)$$

where Mp: market prices of CO_2 offsets (USD/ton CO_2); the carbon market price per ton was specified according to the Carbon Footprint Center (CFC), Heliopolis University, Egypt, on the basis of the average selling price from 2016/2017 to 2021/2022.

The amount of mitigation of CO_2 emissions (Am_{CO_2} , ton/ha) was estimated using the following equation, as cited by [19]:

$$\text{Am}_{\text{CO}_2} = \text{SCS} \times \text{CF} \quad (8)$$

where SCS: soil carbon sequestration, ton/ha; CF: conversion factor of CO_2 emissions from carbon (1 kg C = 3.664 kg CO_2).

The total profit (TP, USD/ha) was calculated as follows:

$$\text{TP} = \text{NR} + \text{PCO}_2 \quad (9)$$

- Statistical Analysis

The experiments were conducted using the randomized block design. The variations between the mean values were compared using the least significant different (LSD) method at the 5% significance level, according to [20].

3. Results and Discussion

The results obtained are discussed according to the following topics:

3.1. Soil Characteristics

3.1.1. Soil Physical and Chemical Analysis

Long-term scrutiny was undertaken to examine the impacts of various farming systems on the soil physical and chemical characteristics over a six-year period. The soil analysis was conducted both before and after the long-term impact and showed apparent the differences between the farming systems, as clarified in Table 1. The results showed that the long-term effects of using compost with biodynamic additives for six years enhanced the soil properties compared to other farming systems. Specifically, the employment of a biodynamic farming approach resulted in a decrease in soil bulk density, alongside an increase in water-holding capacity (WHC), soil organic carbon (SOC), and soil organic matter (SOM).

Table 1. Effect of different farming systems on soil properties.

Measurements	At the Beginning	After Six Years Using Different Farming Systems		
		Biodynamic	Organic	Conventional
Soil bulk density, kg/m ³	1654	1572 (−4.96%)	1586 (−4.11%)	1722 (+4.11%)
Water-holding capacity, %	4.20	5.65 (+1.45%)	5.33 (+1.13%)	4.68 (+0.48%)
pH	7.53	7.40 (−1.73%)	7.20 (−4.38%)	8.10 (+7.57%)
EC, dS/m	1.49	1.58 (+6.04%)	1.61(+8.05%)	1.65 (+10.74%)
SOM, %	0.29	1.51 (+1.22%)	1.32 (+1.03%)	0.71 (+0.42%)
SOC, %	0.17	0.88 (+0.71%)	0.77 (+0.60%)	0.41 (+0.24%)
C/N ratio	4.25	9.78 (+5.53)	9.63 (+5.38)	6.83 (+2.58)
Total N, %	0.04	0.09 (0.05%)	0.08 (+0.04%)	0.06 (+0.02%)
Total P, %	0.09	0.19 (+0.10%)	0.17 (+0.08%)	0.15 (+0.06%)
Total K, %	0.05	0.10 (+0.05%)	0.09 (+0.04%)	0.07 (+0.02%)

After six years of continuous observation, the soil bulk density values were 1572, 1586, and 1722 kg/m³ for the biodynamic, organic, and conventional farming systems, respectively. This indicates a decrease of 4.96 and 4.11% from the initial values when employing the biodynamic and organic farming systems, respectively. In contrast, there was a 4.11% increase observed in the conventional systems. Soils rich in organic matter and carbon have better properties, and soil aggregation and water-holding capacity are increased, while bulk density is decreased. This phenomenon is attributable to the tendency of soils with a fine texture to form porous granules, particularly in the presence of adequate organic matter content. Consequently, such soils exhibit high pore space and low mass density; this negative correlation was in agreement with that in [21]. Using all the farming systems enhanced the WHC, EC, SOM, SOC, C/N ratio, total N, total P, and total K in different proportions compared to the beginning of the experiment. The WHC values were 5.65, 5.33, and 4.68%, and the SOM values were 1.51, 1.32, and 0.71% which corresponded to the SOC values of 0.88, 0.77, and 0.41% for the biodynamic, organic, and conventional farming systems, respectively. Using biodynamic and organic additives reduced the pH value, and the opposite was noticed in the conventional system compared to the beginning of the experiment. Using chemical fertilizers (conventional system) gave the highest soil pH (8.10) over time compared to the other treatments. It has also been proven that the repeated use of organic farming systems results in better soil quality compared to conventional systems [22]. The SOC affects soil nitrogen (N); so, it was noted that the total nitrogen reached the highest

value of 0.09% with the use of biodynamics, while it was 0.08% for the organic system and 0.06% for the conventional system. In light of the above, using a biodynamic farming system led to an enhancement in soil quality compared to the other systems; this result was identical to that of [10], where it was observed to decrease bulk density by 8.71%, while also leading to an increase in WHC of 0.97%, SOM of 0.80%, SOC of 0.47%, total N of 0.03%, total P of 0.04%, and total K of 0.03% compared to a conventional system.

3.1.2. Soil Carbon Sequestration

The impacts of the different farming systems on total organic carbon (TOC) and soil carbon sequestration (SCS) are explained in Table 2. The data indicated that both the TOC and SCS exhibited an increase with the successive farming seasons, which was attributable to the rise in OM content. The average TOC contents using a biodynamic system were 1.36 and 1.55 times higher than those of the organic and conventional systems, respectively. The TOC values ranged from 10.88 to 41.66 tons/ha using a biodynamic farming system, from 9.45 to 36.69 tons/ha using an organic system, and from 8.95 to 21.26 tons/ha using a conventional system. Compost is extensively utilized to enhance soil quality through the sequestration of carbon, which appeared in the calculation of the cumulative carbon uptake in the soil with biodynamic and organic additions. The obtained results were in line with those of [23]. The SCS was increased from 2.41 to 11.84 tons/ha using the biodynamic farming system, from 0.98 to 10.53 tons/ha using an organic farming system, and from 0.48 to 2.79 tons/ha using a conventional system. The impact of the various farming systems on TOC was found to be non-significant during the initial two agricultural seasons. However, its significance gradually increased over the subsequent seasons, eventually reaching a highly significant level. In contrast, the effects of employing different farming systems on SOC were consistently significant and eventually attained a highly significant status across the agricultural seasons.

Table 2. Total organic carbon and soil carbon sequestration using farming systems.

Farming System	Total Organic Carbon, ton/ha						Average	SD
	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022		
T1	10.88 ^a (28.47%)	13.90 ^a (64.19%)	17.64 ^a (108.29%)	22.43 ^a (164.95%)	29.82 ^a (252.14%)	41.66 ^a (391.98%)	22.72 (168.34%)	11.43
T2	9.45 ^b (11.56%)	11.95 ^b (41.07%)	15.46 ^b (82.59%)	19.99 ^b (136.10%)	26.15 ^a (208.89%)	36.69 ^a (333.26%)	19.95 (135.58%)	10.13
T3	8.95 ^b (5.75%)	10.48 ^b (23.74%)	13.12 ^b (54.97%)	15.80 ^b (86.54%)	18.47 ^b (118.17%)	21.26 ^b (151.09%)	14.68 (73.38%)	4.73
LSD, 5%	NS	NS	*	**	**	**		
Soil Carbon Sequestration, ton/ha								
T1	2.41 ^a (28.47%)	3.02 ^a (27.80%)	3.73 ^a (26.86%)	4.80 ^a (27.20%)	7.38 ^a (32.91%)	11.84 ^a (39.71%)	22.59 (14.25%)	14.03
T2	0.98 ^b (11.56%)	2.50 ^b (26.45%)	3.52 ^a (29.43%)	4.53 ^a (29.31%)	6.16 ^a (30.83%)	10.53 ^a (40.27%)	19.99 (11.48%)	11.29
T3	0.48 ^b (5.75%)	1.52 ^b (17.01%)	2.64 ^b (25.24%)	2.67 ^b (20.37%)	2.68 ^b (16.95%)	2.79 ^b (15.09%)	9.03 (6.21%)	3.16
LSD, 5%	**	*	*	**	**	**		

NS: Not statistically significant; *: Statistically significant; **: Statistically highly significant. T1: Biodynamic system; T2: Organic system; T3: Conventional system.

Regarding cumulative soil carbon sequestration (CSCS) using the different farming systems, as depicted in Figure 4, it was clear that the highest value of CSCS was obtained using a biodynamic farming system (33.19 tons/ha), whereas the lowest value was recorded at 12.79 tons/ha using the conventional system after a six-year duration of long-term effects.

Due to the impact of the biodynamic farming system on the increase in the total organic carbon, the soil carbon sequestration increased; thus, the cumulative carbon increased compared to the other systems.

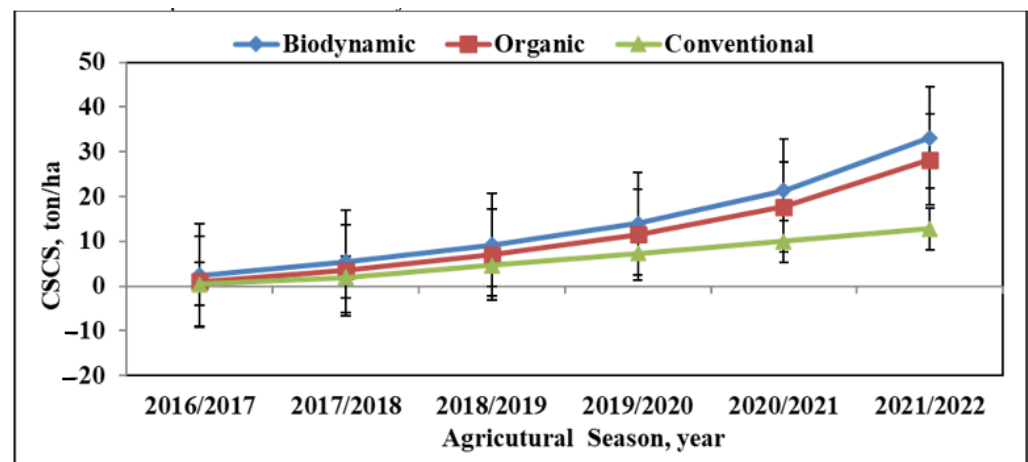


Figure 4. Cumulative soil carbon sequestration using farming systems.

3.2. Environmental Impact

The impact of using farming systems on the mitigation of the environmental impact through the reduction in carbon dioxide emissions over six years is clarified in Table 3 and Figure 5. Changes in soil organic carbon (SOC) play a crucial role in influencing the amount of greenhouse gases emitted into the atmosphere; so, by increasing the SOC using biodynamic systems, as previously mentioned, the cumulative carbon dioxide mitigation increased compared to the other systems; this is compatible with the findings in [24]. The amount of carbon dioxide mitigation increased gradually due to the increase in CSCS, as shown in Table 3; the values ranged from 8.84 to 43.46 tons/ha, from 3.53 to 38.65 tons/ha, and from 1.73 to 10.23 tons/ha using the biodynamic, organic, and conventional farming systems, respectively. The statistical analysis revealed that the impact of farming systems varied initially and became highly significant in the later years of farming.

Table 3. Amount of mitigation of CO₂ emissions using farming systems.

Farming System	Amount of Mitigation of CO ₂ Emissions, ton/ha						Average	SD
	2016/2017	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022		
T1	8.84 ^a (28.47%)	11.10 ^a (27.80%)	13.70 ^a (26.86%)	17.61 ^a (27.20%)	27.09 ^a (32.91%)	43.46 ^a (39.71%)	22.59 (14.25%)	14.03
T2	3.58 ^b (11.56%)	9.17 ^a (26.45%)	12.90 ^a (29.43%)	16.63 ^a (29.31%)	22.62 ^a (30.83%)	38.65 ^a (40.27%)	19.99 (11.48%)	11.29
T3	1.78 ^b (5.75%)	5.59 ^b (17.01%)	9.71 ^b (25.24%)	9.81 ^b (20.37%)	9.83 ^b (16.95%)	10.23 ^b (15.09%)	9.03 (6.21%)	3.16
LSD, 5%	**	*	*	**	**	**		

*: Statistically significant; **: Statistically highly significant; T1: Biodynamic system; T2: Organic system; T3: Conventional system.

Based on the annual amount of the mitigation of carbon dioxide emissions, the cumulative carbon dioxide was calculated, as shown in Figure 5. It was observed that the accumulated CO₂ increased progressively with each growing season, mirroring the trend in cumulative soil carbon sequestration (CSCS). The maximum values for the accumulated CO₂ were 121.80, 103.55, and 46.94 tons/ha using the previous farming systems, in that order. Therefore, using a sustainable biodynamic farming system greatly reduced the

environmental impact, as the cumulative sequestration of carbon dioxide emissions increased by 1.24 and 2.29 times compared to the organic and conventional farming systems, respectively.

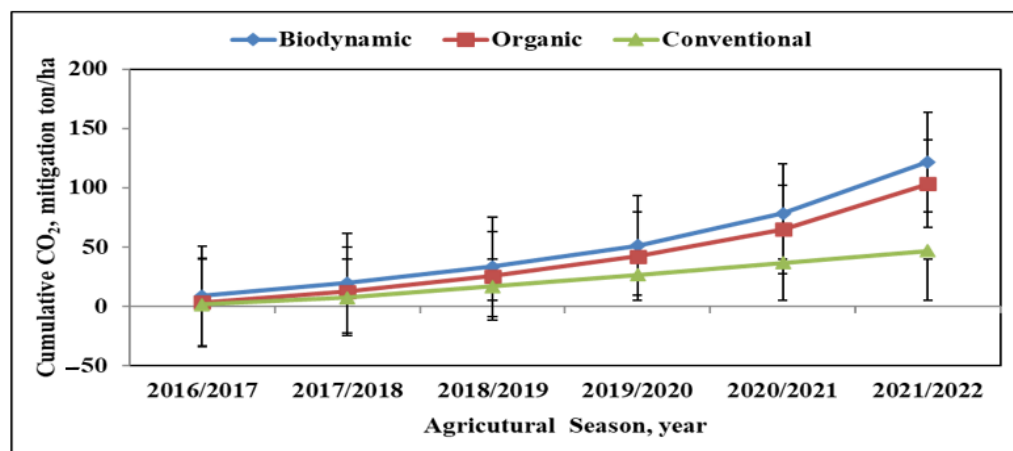


Figure 5. Cumulative mitigation of CO₂.

3.3. Amount of Water Applied

The impact of the biodynamic, organic, and conventional farming systems on the amount of water applied to the maize and faba bean crops is presented in Figure 6. The results indicated that the amount of water applied increased during the agricultural season using the conventional system, while the opposite was observed using the organic and biodynamic systems. This is because using biofertilizers increases the water-holding capacity; thus, the amount of water applied decreases, according to [14]. Organic matter can naturally hold a lot of water; so, the amount of organic matter in the soil directly affects the amount of water that is available to the plant. Compost contains a high percentage of organic matter; so, using compost increases the amount of water that can be retained in the soil. The amount of water applied decreased from 6179 to 6127 and from 3518 to 3461 m³/ha using the biodynamic system and from 6190 to 6144 and from 3530 to 3470 m³/ha using the organic system, while it increased from 6685 to 6775 and from 3763 to 3829 m³/ha using the conventional system for maize and faba bean crops, in that order. The use of biodynamic and organic farming systems saved water at an average of 588.00 and 571.33 m³/ha, with an average rate of 8.73 and 8.48% for the maize crop; they also saved 310.91 and 298.24 m³/ha at a rate of 8.18 and 7.85% for the faba bean crop compared to the conventional system, respectively. Notably, the biodynamic system exhibited the highest percentage of water savings, surpassing the organic system by 0.25% for maize and 0.33% for faba bean crops.

3.4. Crop Yield

The effect of different farming systems over a long-term period of six years on the yield of maize and bean crops is illustrated in Figure 7. The data obtained clarified that the use of chemical fertilizers for maize and faba bean crops at the beginning of the agricultural seasons led to an increase in yield compared to the other systems; this corresponds to the findings in [6]. It was found that the soil fertility was improved as a result of the effect of the organic and biodynamic additions for six years, and this was reflected in the increase in yield. The maize yield ranged from 6.10 to 6.80, from 6.02 to 6.63, and from 6.20 to 6.52 tons/ha; similarly, the faba bean yield ranged from 3.44 to 4.01, from 3.35 to 3.89, and from 3.50 to 3.85 tons/ha under the effects of the biodynamic, organic, and conventional farming systems, in that order. As a result of the improvement of the soil characteristics with the use of the biodynamic system, there was an increase in the maize yield of 1.68 and 0.99% and of 3.25 and 1.57% in the faba bean yield compared to the organic and conventional systems, respectively. Using organic amendments increases soil

organic matter, resulting in increased yields. The obtained results are consistent with the findings in [7,10,25] and are different from those obtained by [6] after long-term effects. The statistical analysis indicated no significant differences in the effects of the farming systems on crop yield.

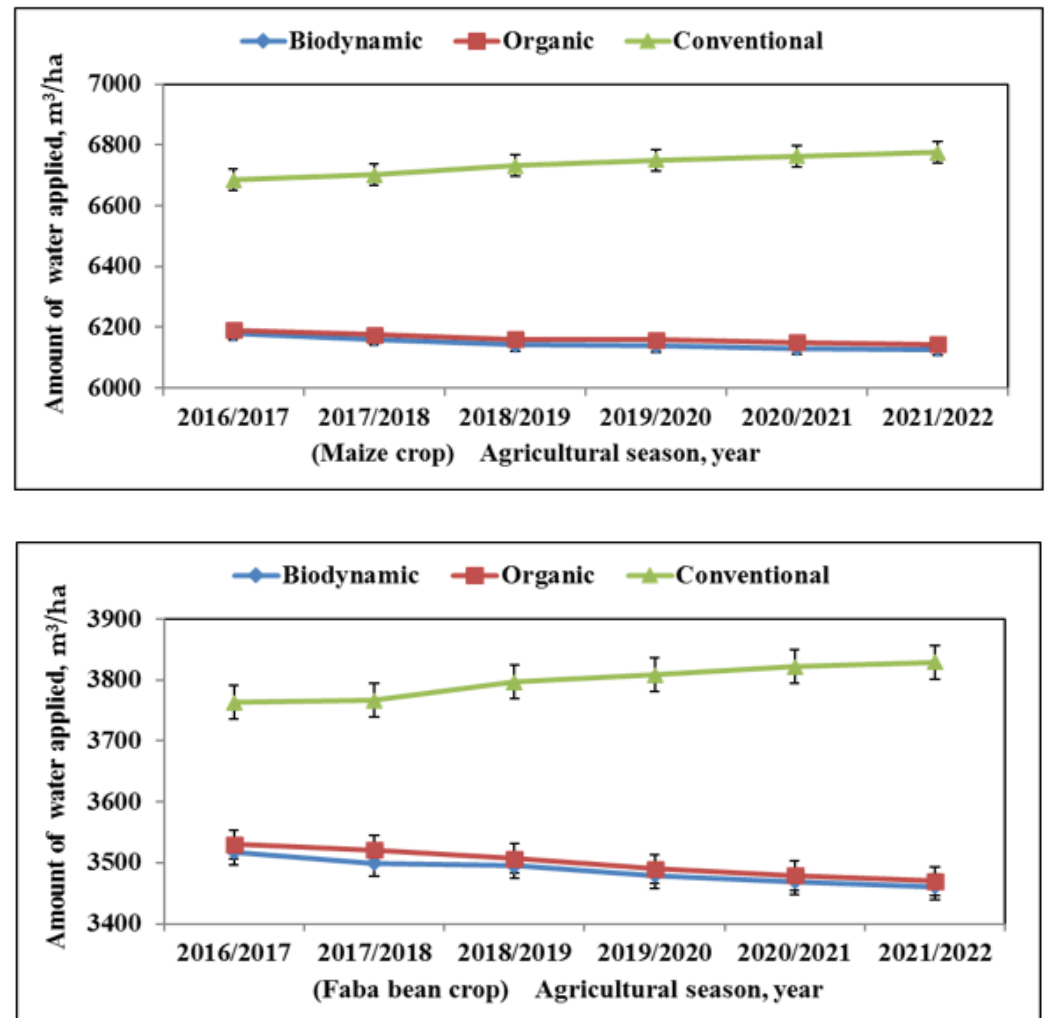


Figure 6. Amount of water applied to maize and faba bean crops using different farming systems.

3.5. Water Use Efficiency

The water use efficiency (WUE) was calculated based on the crop yield and the amount of water applied using the different farming systems, as explained in Figure 8. The data revealed that WUE increased during the growing systems under the influence of farming systems. The WUE values ranged from 0.99 to 1.11 kg/m³, from 0.97 to 1.08 kg/m³, and from 0.93 to 0.96 kg/m³ for the maize crop; however, they ranged from 0.98 to 1.16 kg/m³, from 0.95 to 1.12 kg/m³, and from 0.93 to 1.01 kg/m³ for faba bean crop under the effects of the biodynamic, organic, and conventional farming systems, respectively. From the data obtained, it was found that biofertilizers enhanced WUE, due to the increase in crop yield with a decrease in the amount of water applied. The obtained result agrees with that of [14]. Organic fertilizers can improve soil water storage and retention and, to a certain extent, can coordinate the effect between crop water demand and soil water supply, thus improving WUE [26]. WUE was increased using the biodynamic farming system by 1.96 and 10.67% for the maize crop and by 3.62 and 10.68% for the faba bean crop compared to the organic and conventional farming systems, in that order.

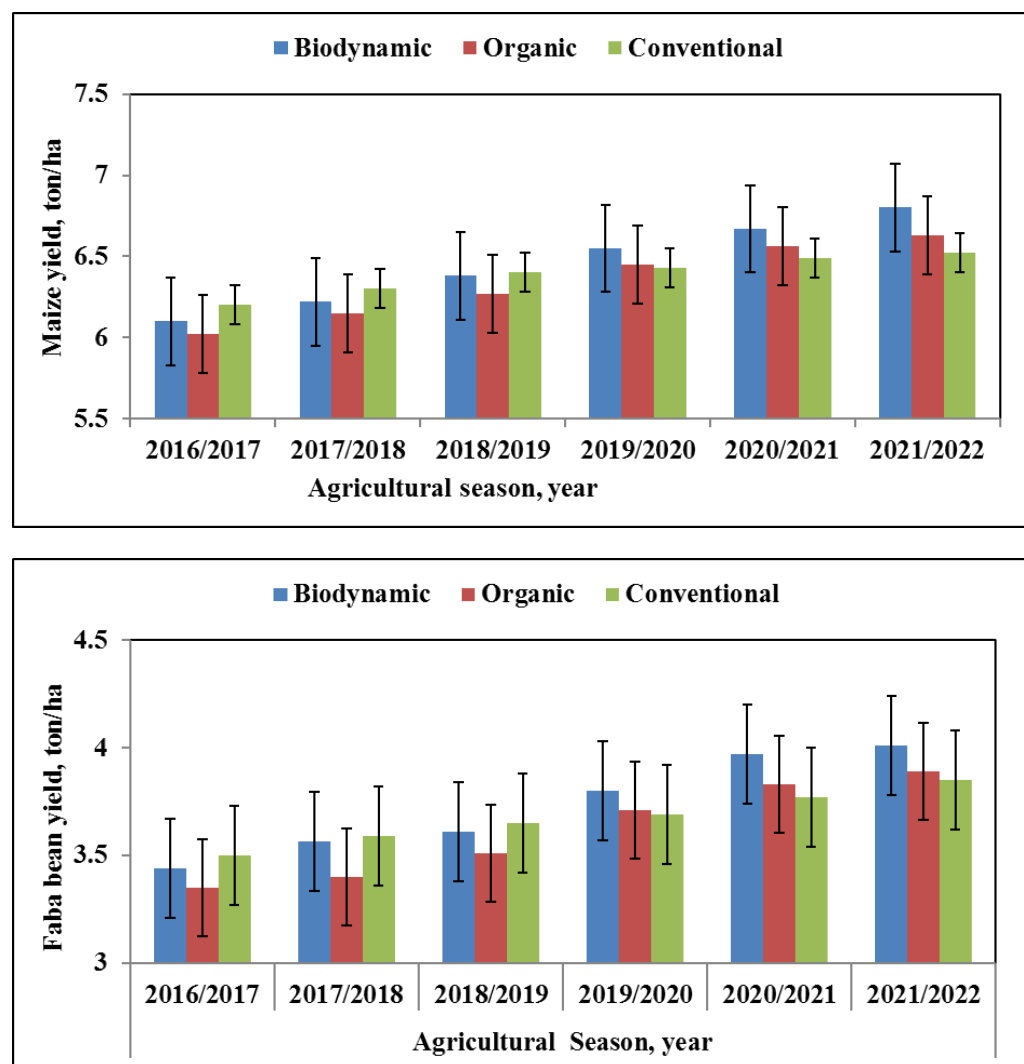


Figure 7. Yield of maize and faba bean crops using different farming systems.

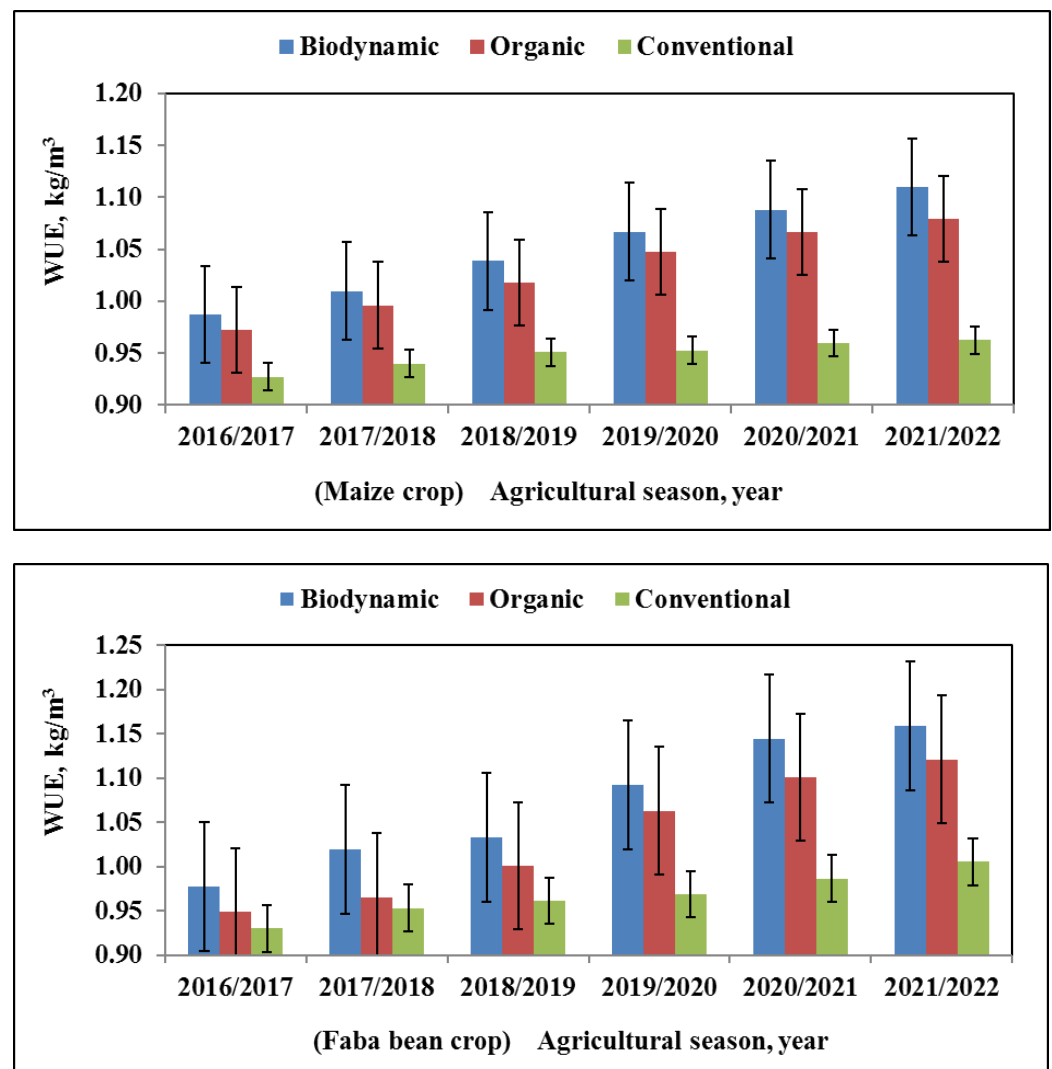
3.6. Cost Estimation

The production cost, total cost, total return, net return, carbon profit, and total net profit were calculated in each growing season under the influence of the biodynamic, organic, and conventional farming systems. In the analysis, the costs of the two crops of maize and faba bean were computed as average values over six years, as shown in Table 4.

As a result of relying only on biopesticides for pest control, with the cost of the other bio-additives, the total cost was higher using a biodynamic farming system compared to other systems. Due to the difference in the total cost relative to the total return of crop yield, the lowest production cost was obtained using the biodynamic, the organic, and then the conventional systems. The production costs were 155.93, 156.33, and 157.62 USD/ton for the maize crop, while they were 280.80, 281.30, and 285.27 USD/ton for the faba bean crop using the same mentioned farming systems, respectively. The highest average peak value was observed using the conventional system, which was attributable to the greater increase rate in total costs compared to productivity. Conversely, the adoption of the biodynamic system resulted in improved soil fertility and increased crop yields, thereby enhancing the total return.

Table 4. Cost estimation of maize and faba bean crops using farming systems.

Crop	Cost Analysis	Farming System		
		Biodynamic	Organic	Conventional
Maize	Production cost, USD/ton	155.93	156.33	157.62
	Total cost, USD/ha	1011.59	997.18	1009.91
	Total return, USD/ha	1921.05	1888.65	1898.61
	Net return, USD/ha	909.46	891.47	888.70
	Carbon profit, USD/ha	323.38	274.93	124.63
	Total net profit, USD/ha	1232.84	1166.4	1013.33
Faba bean	Production cost, USD/ton	280.80	281.30	285.27
	Total cost, USD/ha	1068.06	1037.73	1060.40
	Total return, USD/ha	2047.07	1983.18	2001.66
	Net return, USD/ha	979.01	945.45	941.26
	Carbon profit, USD/ha	323.38	274.93	124.63
	Total net profit, USD/ha	1302.39	1220.38	1065.89

**Figure 8.** Effect of different farming systems on water use efficiency.

Regarding the net return, it was observed that the net return values were 909.46, 891.47, and 888.70 USD/ha for the maize crop; however, they were 979.01, 945.45, and 941.26 USD/ha for the faba bean crop using the biodynamic, organic and conventional farming systems, respectively. Organic farming is more profitable than conventional

systems due to the high prices of the organic products [27]. Still, although the selling price was unified for the farming systems used during this study, the organic and biodynamic farming systems also gave a greater net return than the conventional system. The increase in the net return using the biodynamic system was due to the increase in the total return over the increase in total cost; it increased by 2.02 and 2.34% compared to the organic and biodynamic farming systems, respectively.

Due to the ability of the biodynamic farming system to sequester soil carbon while mitigating CO₂ emissions, the profitability analysis showed that it gave the highest carbon profit (323.38 USD/ha) compared to the other systems; therefore, the use of the biodynamic farming system increased the total net profit by 5.70 and 21.66% for the maize crop and by 6.72 and 22.19% for the faba bean crop compared to the organic and conventional farming systems, respectively.

In light of the preceding findings, it is evident that the adoption of an organic or biodynamic farming system, which relies on biofertilizer technology, results in an increase in the total net profit, despite the stability of the selling price of the final products using the different farming systems; these results are compatible with those obtained by [4,5].

4. Conclusions

Sustainable agricultural practices have emerged as viable options for mitigating the environmental impacts associated with agricultural production. With the goal of maximizing water use efficiency, enhancing crop productivity, and minimizing the environmental impact, the present study investigates the effects of employing a sustainable biodynamic farming system in comparison to organic and conventional farming systems on soil properties, water saving, crop productivity, and environmental–economic considerations over a period of six years. The experimental results obtained revealed that using a biodynamic farming system gave the best conditions in terms of the following criteria compared to the other systems:

- Soil characteristics: It improved the soil physical and chemical properties, and the soil bulk density was decreased by 8.71%, while it increased water-holding capacity by 0.97%, soil organic carbon by 0.8%, soil organic carbon by 0.47%, total N by 0.03%, total P by 0.04%, and total K by 0.03% over six consecutive years compared to a conventional system.
- Irrigation water requirement: The use of a biodynamic system saved water at a rate of 8.73% for the maize crop and 8.18% for the faba bean crop compared to a conventional farming system, and it gave an average increase in water use efficiency of 1.96 and 10.67% for the maize and 3.62 and 10.68% for the faba bean crops compared to the organic and conventional farming systems, respectively.
- Crop yield: The yield was increased by 1.68 and 0.99% for the maize and by 3.25 and 1.57% for the faba bean crop compared to the organic and conventional farming systems, respectively. The effect of the farming systems was non-significant throughout the agricultural seasons.
- Environment: The biodynamic farming system exhibited the highest average soil carbon of 6.16 tons/ha yearly, surpassing the organic system by 13%. This corresponds to an average reduction of 22.45 tons/ha of CO₂ emissions. The impact of the farming systems was highly significant.
- Economy: Despite the stability of the selling price of the final products for all the systems, it decreased the production cost by 0.26 and 1.07% for the maize crop and by 0.18 and 1.57% for the faba bean crop; it increased the net return by 2.02 and 2.34% for the maize crop and by 3.55 and 4.01% for the faba bean crop; this was in addition to the advantage of the system in sequestering and increasing the carbon profit; so, it gave an increase in the total net profit of 5.70 and 21.66% for the maize crop and 6.72 and 22.19% for the faba bean crop compared to the organic and conventional farming systems, respectively.

Considering the various aspects and benefits highlighted earlier, it is imperative that farms currently employing conventional farming methods transition towards more sustainable and eco-friendly practices. Among the viable options, the biodynamic farming system emerges as a significant candidate from the perspective of sustainable agriculture.

To further enhance the efficiency of the drip irrigation system, the author's future work will extend to the following:

- Utilizing microturbines in the irrigation system with the best efficiency of micro-hydropower to increase sustainable energy generation using different crops with the application of Internet of things (IoT).

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