agronomy

MDPI

*Article*

# Enhancing Sustainability in Intensive Dill Cropping: Comparative Effects of Biobased Fertilizers vs. Inorganic Commodities on Greenhouse Gas Emissions, Crop Yield, and Soil Properties

**Encarnación Martínez-Sabater [1], María Dolores Pérez-Murcia [1], Francisco Javier Andreu-Rodríguez [1], Luciano Orden [1,2,*], Enrique Agulló [1], José Sáez-Tovar [1], Juan Martínez-Tome [1], María Ángeles Bustamante [1] and Raul Moral [1]**

1 Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH), GIAAMA Research Group, Universidad Miguel Hernández, Carretera de Beniel Km 3.2, 03312 Orihuela, Spain
2 Estación Experimental Agropecuaria INTA Ascasubi (EEA INTA Ascasubi), Ruta 3 Km 794, Hilario Ascasubi 8142, Argentina
* Correspondence: l.orden@umh.es



**Citation:** Martínez-Sabater, E.; Pérez-Murcia, M.D.; Andreu-Rodríguez, F.J.; Orden, L.; Agulló, E.; Sáez-Tovar, J.; Martínez-Tome, J.; Bustamante, M.Á.; Moral, R. Enhancing Sustainability in Intensive Dill Cropping: Comparative Effects of Biobased Fertilizers vs. Inorganic Commodities on Greenhouse Gas Emissions, Crop Yield, and Soil Properties. *Agronomy* **2022**, *12*, 2124. https://doi.org/10.3390/agronomy12092124

Academic Editor: Bertrand Hirel

Received: 25 July 2022
Accepted: 6 September 2022
Published: 7 September 2022



**Abstract:** The treatment and valorization of organic solid waste has become a promising alternative to increase intensive crop productivity while reducing its environmental impact. Currently, reusing improved organic waste as novel biofertilizers is a vital tool to adapt semiarid agricultural regions to climate change, but this has been scarcely studied in aromatic crops. The present study aims to assess the greenhouse gas emissions, soil properties, and crop yield of a dill crop using a drip irrigation system with a normalized N application rate of 160 kg N $ha^{-1}$. We compare eight different fertilizing scenarios grouped into organic-based (manures and compost) and inorganic-based inputs (NPK commodities and slow-release formulations). GHG fluxes were measured during the 57-day fertigation period using static chambers. Key soil properties were measured previous to fertilizer applications and at harvest, coinciding with crop yield estimations. An increase in soil organic carbon was observed with stabilized organic treatments at 0–20 cm soil depth. The results show that stabilized organic-based materials lowered $NO_3^-$ concentrations in dill biomass more than synthetic fertilizers, producing similar yields to those with synthetic fertilizers. In general, $N_2O$ emissions were positively affected by the treatments. Local specific emission factors for $N_2O$ were determined (0.08%), which were substantially lower than the default value (0.51%) of IPCC. The cumulative $CO_2$ emissions were high in all the organic scenarios compared to the control treatment (277 kg C-$CO_2$ $ha^{-1}$), probably due to differences in labile organic C contents. Organic-based treatments showed multiple positive effects on crop quality, crop yields, and GHG mitigation potential. The use of organic amendments is an optimized N fertilizing strategy to promote circular economy and sustainability.

**Keywords:** *Anethum graveolens* L.; organic amendments; GHG; drip irrigation

## 1. Introduction

*Anethum graveolens* L. (dill) is an aromatic herbaceous plant that originated as far east as India, although some authors say it is native to the Mediterranean [1]. It is cultivated industrially using improved varieties in Central and Eastern European countries, the Middle East, and North America. However, it can be found spontaneously in the Mediterranean area and some parts of Asia [2]. Cultivating aromatic plants is a growing industry that can be economically relevant (due to stable prices and long-term profitability) and promote rural development, especially to meet the increasing global demands of the food, pharmaceutical, and cosmetic industries. Dill is usually found in warm to temperate climates, but it can also withstand slightly colder temperatures. Its spatial distribution reaches up to 600 m in altitude, and it prefers sunny, light, humid, fertile, well-drained soils [3]. It is a crop with a short vegetative cycle; the duration of the crop is usually between 50 and 80 days after sowing to obtain leaves and between 100 and 120 days to obtain fully developed seeds. The fertilizing requirements of dill in intensive plantations are usually performed by fertigation at a rate of 120 kg N $ha^{-1}$, 50 kg P $ha^{-1}$, and 50 kg K $ha^{-1}$ to obtain the green part of the plant. Nitrogen (N) is the limiting criterion for calculating fertilizer dosage [4].

Intensive production systems in European Mediterranean regions contribute to the loss of soil fertility. Increasing threats have pushed soils to the critical limits of their ecosystems [5]. Reversing the trend of the soil organic carbon (SOC) loss resulting from long periods of agronomic activity with mineral fertilization can help improve soil health. The possibility of increasing SOC content by changing agronomic practices can play an essential role in facing climate change [6]. Maintaining organic matter (OM) is important not only to capture and mitigate greenhouse gases (GHG) [7] but also to significantly influence the physical, chemical, and biological properties of soil [8]. Pardo et al. [9] estimated an increase in SOC of 0.13 Mg $ha^{-1}$ $yr^{-1}$ if the entire agricultural surface of the Mediterranean region of Spain was amended with available, underutilized, exogenous organic materials (urban waste and composted agroindustrial by-products).

The valorization of organic matter as a source of nutrients is a strategy to reduce dependence on chemical fertilizers. Using stabilized and mature organic amendments can maintain and even increase C stocks in soils and improve N availability to crops [10]. As a result, they are nowadays very important inputs to consider to tackle post-COVID-19 recovery and the consequences of the global energy shortage [11]. With the long-term use of bio-stabilized organic amendments, the residual effects on crop production and soil properties can last for several years, as only a fraction of N and other nutrients are available to plants after application [12]. Using organic amendments would contribute to substituting inputs for the agroecological transition of aromatic crops, which consumers currently demand. In addition, producing compost from organic waste would increase the move toward a circular economy [13]. In this way, we can help establish better fertilizing strategies for agronomy, the environment, and sustainability.

Also, for GHG emissions, N-balanced fertilization is proposed as a strategy to reduce $N_2O$ emissions in Mediterranean agricultural systems without affecting crop yields [14]. An additional mitigation effect could be achieved by applying already existing N (organic fertilizer) when possible or with the use of nitrification and urease inhibitors [15]. However, the incorporation of fertilizers (either organic or inorganic) with high ammonia ($NH_4^+$) concentration and irrigation promotes nitrification and $O_2$ consumption ($CO_2$ release), generating suboxic conditions, increasing nitrifier denitrification ($NO_2^-$ accumulation promotes reduced $N_2O$) [16]. There is a scarcity of data on emissions in aromatic crop production systems, so more field studies should be conducted to verify the emission factors proposed by other authors in intensive crops [17,18].

The main objective of this work is to comparatively evaluate the effect of different fertilizing materials (bio-stabilized organic, fresh organic, and inorganic) on a dill crop and to study the different conditions generated by each of them on the crop itself, the soil, and the GHGs emitted into the atmosphere during cultivation. The starting hypotheses were that: (i) fertilization treatments with N isodose have equal crop yields, (ii) GHG emissions during the cultivation period are larger from conventional fertilization than from organic amendments, and (iii) organic amendments improve soil properties more than inorganic fertilization.

## 2. Materials and Methods

### 2.1. Experimental Site

The study was carried out in a productive commercial field in Librilla, Murcia, Spain (37°55′ N, 1°17′ W; 180 m a.s.l.). The climate in this area is classified as warm semiarid according to the climate classification (Köppen) due to scarce annual rainfall (303 mm).

During the field experiment (57 days), the average temperature was 17.4 °C, two rainfall events (total of 13.5 mm) were recorded, and the average relative humidity was 63.2%. The weather data were obtained from a meteorological station belonging to the Agro-meteorological Information System of the Murcia Region (SIAM-IMIDA) (Figure 1).

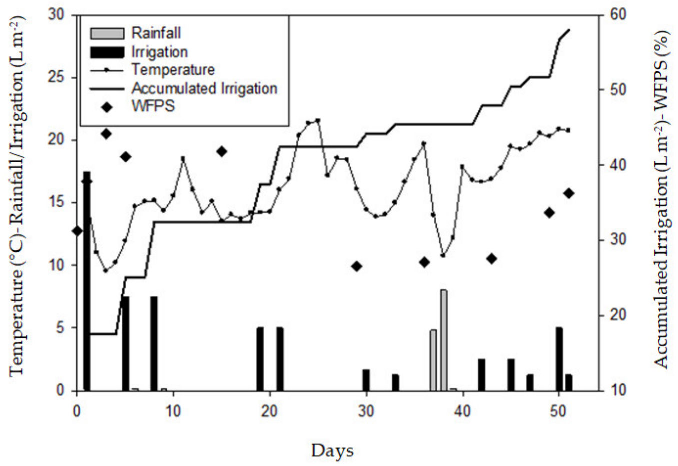


**Figure 1.** Mean temperature (°C), WFPS: water-filled pore space (%), rainfall (L $m^{-2}$), daily irrigation (L $m^{-2}$), and accumulated irrigation (L $m^{-2}$) at the experimental site.

The soil at the field site is Calcaric Fluvisol [19], clay loam (34.3% sand, 12.6% silt, 53.1% clay; color 10YR 7/3 light brown). The (0–30 cm depth) physicochemical characteristics of the soil are: 0.63% SOC, 0.08% total N (TN), 117 mg $kg^{-1}$ N-$NO_3^-$, 47.2 mg $kg^{-1}$ extractable phosphorus (Pe), 0.34 dS $m^{-1}$ electrical conductivity (EC), pH 8.4, 1.44 kg $m^{-3}$ bulk density, 13.9 meq 100 $g^{-1}$ cation exchanging capacity (CEC), and 259 g $kg^{-1}$ water holding capacity (WHC).

### 2.2. Crop Management

The *Anethum graveolens L.* seeds (var. N18 SR22) were direct-seeded mechanically on 22nd March and hand harvested on 16th May (55-day growing season). The sowing density was 200 plants per $m^{-2}$. Soil and seedbed preparation (1.40 m; 30 cm between beds) were performed mechanically. Drip irrigation was installed with 4 L $ha^{-1}$ droppers, with the total irrigation applied over 579 $m^3$ $ha^{-1}$ and a cumulated irrigation of 57.9 L $m^{-2}$ (Table 1). The water quality shows an adequate Ca:Mg ratio and a moderate–high risk of salinization [20]. Pest and disease management was performed conventionally with authorized products, respecting the recommended use and dosage.

**Table 1.** Physicochemical characteristics of the irrigation water used in the experiment.

| pH | EC | $Na^+$ | $HCO_3^-$ | $Cl^-$ | SAR |
|---|---|---|---|---|---|
| | (dS $m^{-1}$) | (mg $L^{-1}$) | (mg $L^{-1}$) | (mg $L^{-1}$) | |
| 8.64 | 2.96 | 243 | 192 | 408 | 4.2 |

EC: electrical conductivity; SAR: sodium adsorption ratio. The table shows the average of a composite sample.

### 2.3. Experimental Design and Treatment

A completely randomized design with four replicates was established. Eight fertilizing treatments were applied in the plots (5.93 $m^2$) according to a normalized N application rate of 160 kg N $ha^{-1}$: (i) compost (HP), prepared from the mixture of wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings (40–60% d.m.w.); (ii) compost (HP-2), made from a mixture of agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings (40–60% d.m.w.); (iii) vermicompost (VT), produced from cow manure; (iv) biosolid (LO) from the wastewater treatment plant in Orihuela (Alicante, Spain);

(v) cow manure (EST), from a dairy farm with 500 heads of producing cattle; (vi) NPK inorganic fertilizer (15-15-15, N-$P_2$O5-$K_2O$ richness in %) (NOLI) with 85.15% ammoniacal N; (vii) NPK + DMPP inorganic fertilizer (LI-2), (21-8-11, N-$P_2O_5$-$K_2O$ richness in %), with slow-releasing capacities linked to 0.8% DMPP (3,4- dimethylpyrazole phosphate) as a nitrification inhibitor; (viii) fertigation (FERTI), combining two different strategies of fertilization, NPK (14-7-17, N-$P_2O_5$-$K_2O$ richness in %) for basal fertilization and liquid fertilizer injected via fertigation applying the remaining N during the growing season; and control (B), plots without fertilization. All the treatments were applied manually with a rake to deeply fertilize the soil (0–10 cm) before planting.

### 2.4. Soil Analysis and Crop Measurements

The physicochemical and chemical characteristics of the fertilizers and amendments used were analyzed according to the methods described by [21]. Inorganic fertilizers (NOLI and LI-2) were analyzed following the methods described in Regulation (EC) 2003/2003 regarding fertilizers (Table 2). All the analyses were made in triplicate. The effects of the fertilizers on the soil samples were taken in each plot at 0 and 55 days after application to determine the residual effects of the organic amendments in the soil. The samples were collected from topsoil (0–20 cm), then air-dried and sieved to 2 mm. The pH was measured in a 1:2.5 soil:water (*w*/*v*) extract and the electrical conductivity (EC) in a 1:5 (*w*/*v*) soil:water extract [22]. The oxidizing organic carbon (COT) was measured following Wakley and Black [23]. The N total Kjeldahl (TN), nitrate ($NO_3^-$-N), and ammonium ($NH_4^+$-N) were analyzed in soil samples following the methods used by [21]. Available P (Pe) was determined colorimetrically using the method of [24].

**Table 2.** Characteristics of the fertilizers used in the experiment (dry weight basis).

| Parameters | | Treatment | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | HP | HP-2 | VT | LO | EST | NOLI | LI-2 |
| Moisture | (%) | 51.4 | 34.9 | 27.6 | 77.2 | 76.7 | nd | nd |
| pH | | 5.8 | 7.4 | 8.2 | 6.8 | 9.6 | nd | 5.5 |
| EC | (dS $m^{-1}$) | 9.0 | 8.3 | 4.1 | 4.0 | 6.9 | nd | nd |
| COT | (g $kg^{-1}$) | 314 | 371 | 173 | 332 | 408 | nd | nd |
| TN | (g $kg^{-1}$) | 31.9 | 28.7 | 14.7 | 49.7 | 27.4 | 150 | 210 |
| $NO_3^-$-N | (g $kg^{-1}$) | 4.66 | 1.20 | 0.92 | 0.04 | 0.03 | 20 | 99 |
| $NH_4^+$-N | (g $kg^{-1}$) | 0.06 | 0.07 | 0.02 | 2.16 | nd | 130 | 111 |
| COT/TN | | 9.8 | 12.9 | 11.8 | 6.7 | 23.4 | nd | nd |
| P | (g $kg^{-1}$) | 11.1 | 4.1 | 8.6 | 13.5 | 3.0 | 65.5 | 34.8 |
| K | (g $kg^{-1}$) | 11.4 | 22.5 | 10.2 | 3.5 | 27.7 | 125 | 91.6 |
| Na | (g $kg^{-1}$) | 7.4 | 10.7 | 4.4 | 2.3 | 9.2 | nd | nd |

EC: electrical conductivity; COT: total organic carbon; TN: total nitrogen; nd: not determined. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. The table shows the average of a composite sample.

The plant material sampling was carried out before flowering (40–50 cm height). All the plants from each plot were harvested, cutting all the aerial biomass of the dill, which was weighed to determine the yield on a fresh weight basis (kg $m^{-2}$). The dry matter was determined by drying plant samples in an oven at 45 °C to constant weight (kg $m^{-2}$).

The mineral composition of the plants was established using nitric perchloric acid digestion [25]. The samples were made in triplicate. The carbon and N in the tissue samples were measured in an automatic elemental micro analyzer (EuroVector Elemental Analyser). P was measured in a spectrophotometer UV-V; K and Na were determined using a photoelectric flame photometer. The $NO_3^-$-N in fresh leaves was determined following the European Union (2006) regulation and the EN12014–4: 2005 Standard Reference [26].

The nutrient extraction in plant aerial tissues was measured and expressed as kg ha$^{-1}$ to establish the overall effect of the treatments.

Nitrogen use efficiency (NUE; expressed as the percentage of the applied N-fertilizer taken up in the dill) was calculated using the N difference method, with the total N of the unfertilized treatment as the control [27]. Phosphorus and potassium use efficiency (PUE and KUE, respectively) were calculated in the same way.

### *2.5. GHG Measurements*

Static chamber methods were used to measure the gaseous emission surface fluxes of $CO_2$, $CH_4$, and $N_2O$ during the experiment. The gas samples were taken on days 0, 1, 2, 3, 5, 8, and then weekly [28], with a total of 12 samplings. Opaque chambers (18.3 L and 0.108 m$^2$) placed in the center of each plot were used for this purpose. The gas was collected from the headspace of each chamber at 0, 30, and 60 min with 60 mL syringes injected into gas-tight 12 mL pre-evacuated vials with overpressure [29]. The gas samples were always taken during the same hours of the morning (10–12 a.m.) to minimize the effects of diurnal variations on the emissions. The concentrations of gas in the samples were established using a gas chromatograph (HP 6890, Agilent Technologies) equipped with an electron-capture detector (ECD) to analyze $N_2O$ and a flame-ionization detector (FID) to measure $CO_2$ and $CH_4$. Three gas standards comprising a mixture of gases (high with 1500 ± 7.50 ppm $CO_2$, 10 ± 0.25 ppm $CH_4$, and 2 ± 0.05 ppm $N_2O$; medium with 600 ± 5.50 ppm $CO_2$, 5 ± 0.15 ppm $CH_4$, and 1.5 ± 0.03 ppm $N_2O$; and low with 200 ± 1 ppm $CO_2$, 1 ± 0.05 ppm $CH_4$, and 1000 ± 25 ppb $N_2O$) were used to establish a standard curve ($R^2$ = 0.99) for each gas [30].

The flow rate emissions (mg m$^{-2}$ day$^{-1}$) on the surface of the soil were calculated from the changes in gas concentrations during the sampling period (60 min) following [31]. The cumulative gas emissions during the sampling period were calculated by averaging the flux in two successive determinations and multiplying that average flux by the length of the period between samplings [32]. $N_2O$ EF was calculated following Aguilera et al. [33]. These parameters indicate the proportion of the N applied in fertilizer released as $N_2O$ after discounting the emissions from the control treatment without fertilization. Yield-scaled $N_2O$ emissions were expressed as the ratio of the amount of $N_2O$-N emitted to the uptake of N by the crop tissue [34].

Finally, the total GHG emissions were estimated as carbon dioxide equivalents ($CO_2$eq). The net cumulative $CO_2$ emissions were added to the $CH_4$ and $N_2O$ emissions from each treatment previously converted to $CO_2$eq using a global warming potential value of 27.2 and 273, respectively [35].

### *2.6. Statistical Analyses*

Analyses of variance at $p < 0.05$ were performed for all the variables of the experiment. Daily fluxes were analyzed using a generalized linear mixed model, with the fertilizer treatments and sampling occasions as fixed factors, while each plot was considered a random factor. The Least Significant Difference (LSD) test was used for multiple comparisons between the means. Differences between treatments were analyzed using the LSD Fisher contrast ($p < 0.05$). The data distribution normality of the GHG fluxes and soil variables was verified using the Kolmogorov–Smirnov test. All the analyses were performed using the Infostat v.2021 statistical software package [36].

## 3. Results

### *3.1. Soil Properties*

The effects of the fertilizing treatments on soil pH at the beginning of dill cultivation showed an initial edaphic condition with a slightly basic pH. Soil pH values decreased significantly compared to the control, tending mostly to basic values. The soil pH in all the treatments decreased slightly in the later sampling (day 55) with the incorporation of the fertilizing treatments (Table 3). This decrease was less marked in the HP compost treatment because this fertilizer had the lowest pH value in the trial (5.8). Carbonates and limestone in the soil have a buffer effect, making the soil resistant to pH changes.

**Table 3.** Effect of fertilizing treatments on soil properties.

| Treatment | pH | | EC ($dS\ m^{-1}$) | | Pe ($mg\ kg^{-1}$) | | TN ($g\ kg^{-1}$) | | $NO_3^-$-N ($mg\ kg^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 d | 55 d | 0 d | 55 d | 0 d | 55 d | 0 d | 55 d | 0 d | 55 d |
| B | 8.39 c | 7.99 bc | 0.33 a | 0.57 b | 62 ab | 77 b | 0.72 a | 0.67 a | 18 a | 11 a |
| HP | 7.94 a | 7.97 abc | 0.58 b | 0.67 c | 76 cd | 92 cd | 1.14 d | 0.92 d | 60 de | 23 b |
| HP-2 | 8.11 c | 8.04 bc | 0.51 b | 0.59 bc | 82 cde | 85 cd | 1.01 c | 0.82 bc | 55 cd | 18 ab |
| VT | 8.18 c | 8.06 c | 0.57 b | 0.66 c | 180 g | 137 e | 1.12 d | 0.84 cd | 52 c | 14 a |
| LO | 8.18 c | 8.17 d | 0.37 a | 0.59 bc | 72 bc | 85 bc | 0.95 c | 0.85 d | 28 b | 31 c |
| EST | 8.26 c | 7.99 bc | 0.39 a | 0.57 bc | 89 de | 87 bc | 0.82 cd | 0.83 d | 23 ab | 13 a |
| NOLI | 8.29 c | 7.87 a | 0.67 c | 0.90 d | 105 f | 102 d | 0,94 c | 0.78 c | 20 a | 50 d |
| LI-2 | 8.19 c | 7.85 a | 0.73 d | 0.56 b | 93 fe | 96 cd | 1.04 c | 0.83 d | 65 e | 60 e |
| FERTI | 8.22 bc | 8.18 d | 0.32 a | 0.45 a | 51 a | 64 a | 0.67 a | 0.72 b | 17 a | 78 f |
| *F-anova* | 7.7 *** | 14.4 *** | 57.3 *** | 29.3 *** | 133 *** | 41.1 *** | 45.71 *** | 8.35 *** | 165 *** | 191 *** |

EC: electrical conductivity; Pe: extractable phosphorus; TN: total Kjeldahl N; $NO_3^-$-N: nitrate. 0 d: 0 days; 55 d: 55 days; HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. *** Significant difference between treatments at $p < 0.001$. Different letters within a column indicate significant differences between treatments ($p < 0.05$).

All the treatments increased the salinity range of the soil. This effect was lower in treatments where organic amendments were applied. The solid inorganic (NOLI and LI-2) and bio-stabilized organic (HP, HP-2, and VT) treatments increased the EC of soluble nutrients compared to the control at the beginning of the experiment (day 0). However, the soil EC value of the fresh organic treatments showed no significant statistical differences from the control.

At the beginning of the trial, all the soils showed a significantly higher Pe concentration than the control treatment, except for the FERTI treatment, as was expected. At the end of the experiment, the NOLI, LI-2, VT, and HP treatments increased the Pe levels in the soil compared to the control, with VT presenting a significantly higher value than the rest.

The TN content increased significantly for all the applied treatments compared to the control soil, except for the FERTI treatment. Since the fertilization of the fertigation crop is carried out gradually during the crop cycle, at the beginning of the experiment, the NPK content was similar to the control. The increase in TN from the FERTI treatment was very slight since the N supply is mainly in the form of $NO_3^-$-N, which is assimilated by the plant and not detected in the NT Kjeldhal measurement.

Regarding the evolution of the $NO_3^-$-N contents in the soil, an increase was observed in all the plots, except for the inorganic fertilizer (NOLI and FERTI). The LI-2 treatment showed the highest increase, which was expected since it is the material with the highest inorganic form of N. Compost and VT also obtained a statistically higher value than the control (B). At 55 days into the experiment, the control soil, stabilized organic (HP, HP-2, and VT), and EST treatments reduced their $NO_3^-$-N content: significantly so in the case of the EST treatment. However, the soil to which the higher $NH_4^+$-N treatments (NOLI and LO) were applied had higher $NO_3^-$-N concentrations at the end of the trial. This indicates that an intense nitrification process had taken place in the soil, allowing the biotransformation of part of the N.

The results obtained for soil organic carbon, SOC, show significant statistical differences from the soil without treatment (B) and the soil amended with composts and vermicompost at day 0 of the experiment. These were the only ones that increased the percentage of SOC in the soil (Figure 2). In particular, the SOC value of the VT treatment (0.95%) was much higher than the fertigation treatment (0.60%). However, there are no statistical differences between the control, inorganic, and fresh organic treatments (LO and EST). At the end of the experiment (day 55), an increase in SOC was observed in most of the organic treatments.

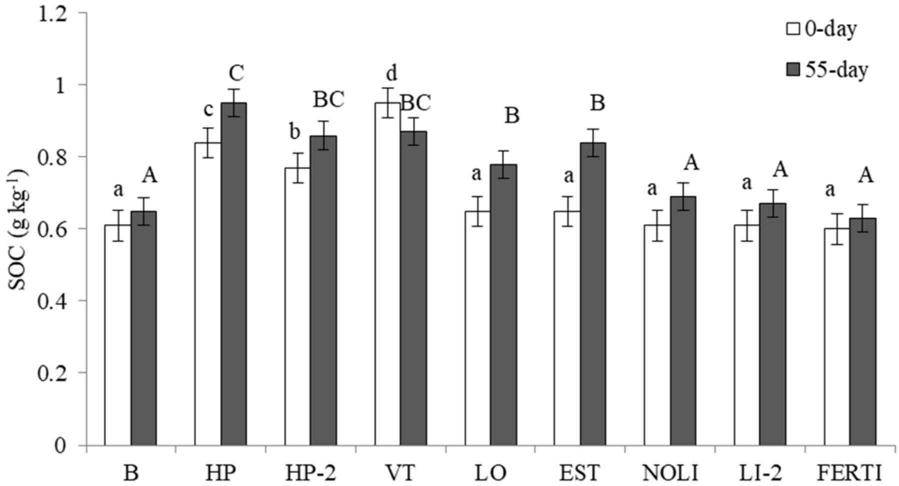


**Figure 2.** Evolution of soil organic carbon during the experiment. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. Different letters within a column indicate significant differences between treatments ($p < 0.05$). Bars represent the standard error of the mean.

### 3.2. GHG Emissions

The GHGs measured in the soil surface of the dill crop across the 57-day monitoring period were influenced by the different fertilizing treatments applied ($p < 0.0001$). The $CO_2$ emissions during the first 10 days were very high for the VT (62 kg $CO_2$-C ha$^{-2}$ d$^{-1}$) and LO (65 kg $CO_2$-C ha$^{-2}$ d$^{-1}$) treatments (Figure 3a). The VT emissions then decreased to values similar to all the treatments, and the LO treatment emissions remained high until day 25. In addition, the LO and VT total cumulated emissions (382 and 349 kg $CO_2$-C ha$^{-1}$, respectively) were able to stimulate the soil microbiota through the contribution of labile nutrients, causing an increase in their metabolic activity at the beginning of the trial. This was reflected in greater $CO_2$ production and emissions. The results for cumulative $CO_2$ emissions were variable, with the FERTI crop obtaining the lowest cumulative emissions (195 kg $CO_2$-C ha$^{-1}$) without significant differences from the control, NOLI, and HP plots.

The LO treatment had the highest $N_2O$ fluxes (1.81 kg $N_2O$-N ha$^{-2}$ d$^{-1}$), followed by the NOLI treatment (0.32 kg $N_2O$-N ha$^{-2}$ d$^{-1}$). $N_2O$ peaks were observed from the LO treatment on days 7 (13.46 mg $N_2O$-N m$^{-2}$ d$^{-1}$) and 21 (7.25 mg $N_2O$-N m$^{-2}$ d$^{-1}$), while the NOLI treatment only showed fluxes on day 7 (3.06 mg $N_2O$-N m$^{-2}$ d$^{-1}$) (Figure 3b). Daily and cumulative $N_2O$ emissions were reduced for most treatments and were mainly associated with nitrification processes, as fertilizers with higher N-$NH_4^+$/N-$NO_3^-$ ratios (LO, NOLI, and LI-2) showed higher emission fluxes, especially during the first 30 days of the experiment. From day 30 onwards, there were no statistically significant differences between treatments, probably due to the reduced presence of $N_2O$ precursors (labile C and nitrate) and the increased demand for $NO_3^-$N and water by the plants, which reduced $N_2O$ emissions. The highest yield-scaled $N_2O$ emissions were measured for LO, followed by NPK, compared to the other fertilizing scenarios (Figure 4).

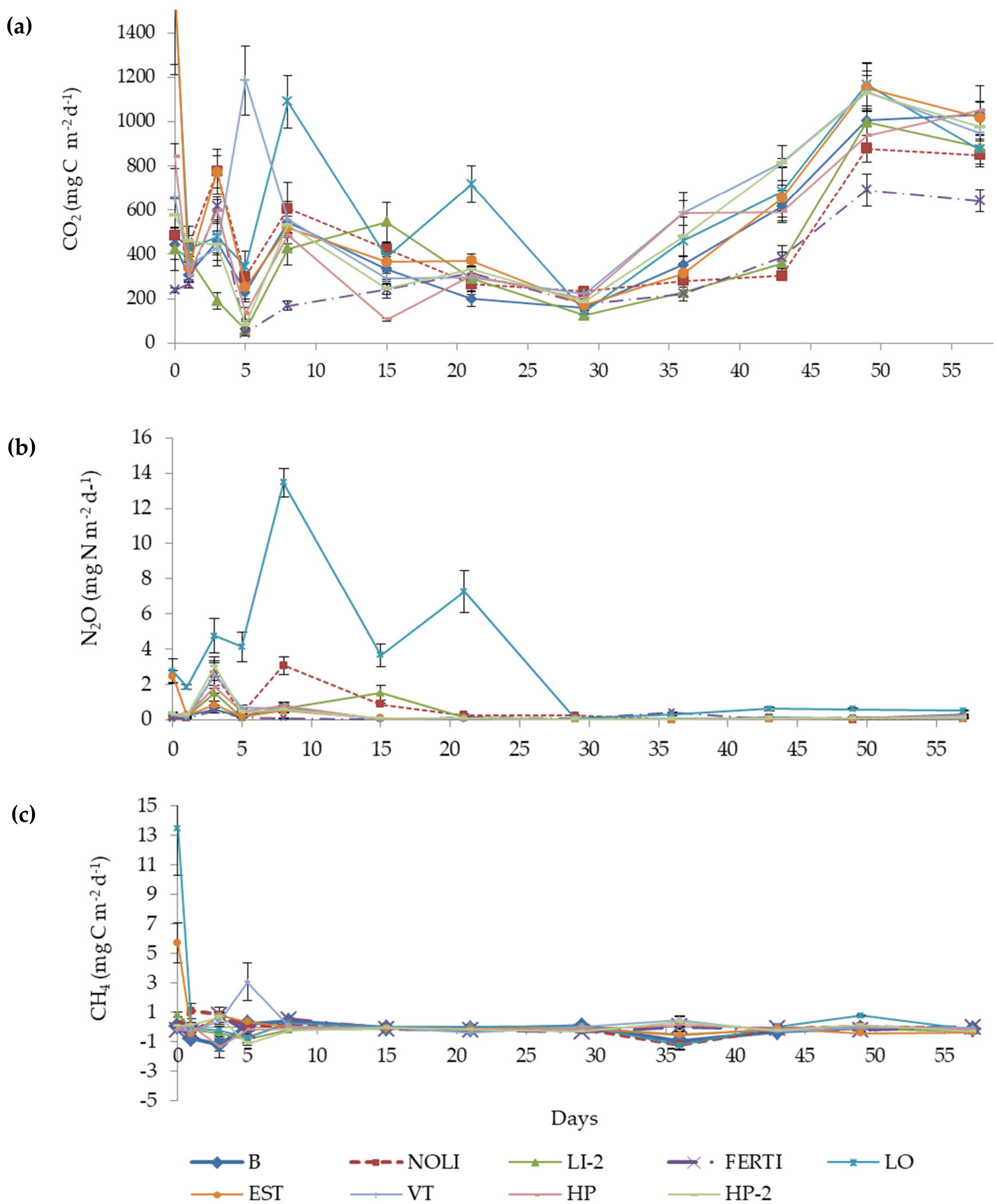


**Figure 3.** Daily fluxes of (**a**) $CO_2$, (**b**) $N_2O$, and (**c**) $CH_4$ from treatment applications during the 55-day monitoring period. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. Bars represent the standard error of the mean.

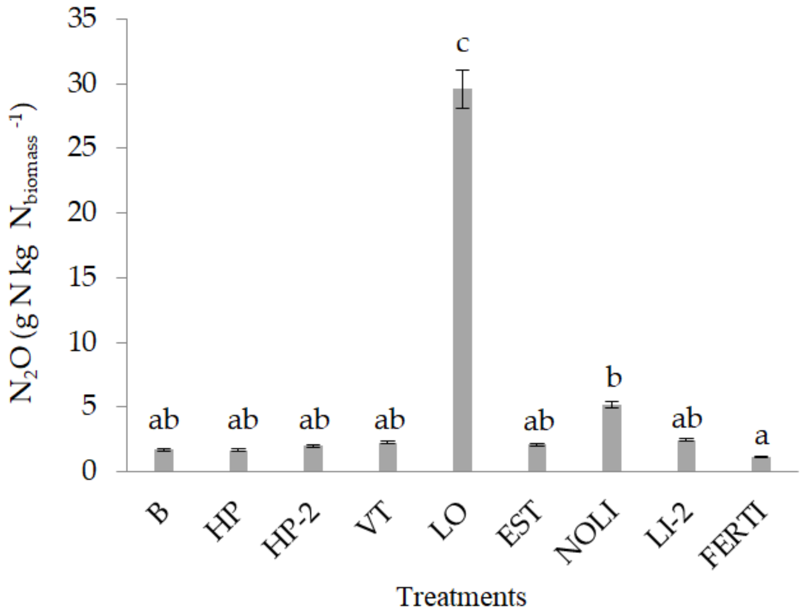


**Figure 4.** Yield-scaled $N_2O$ according to treatment. Different letters indicate significant differences between treatments ($p < 0.05$). Bars represent standard errors. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation.

Although significant differences were found between the treatments in methane ($CH_4$) emission flux, there was a general sink effect (negative cumulative emission balance) in all the fertilizing scenarios except for LO (0.16 kg C-$CH_4$ ha$^{-1}$) and VT (0.06 kg C-$CH_4$ ha$^{-1}$). These showed reduced positive cumulative $CH_4$ emissions. In our study, and in most of the studies mentioned above, conditions favoring this effect normally appeared during the first part of the experiment (Figure 3c)

The organic fertilizers produced significantly lower $CO_2$eq than LO, NOLI, and LI-2 (Table 4). The non-stabilized organic amendments and non-specialized inorganic fertilizers produced significant N losses as $N_2O$. However, LO had significant increases compared to the other treatments (up to six times higher than the nearest treatment in terms of GWP). Vico et al. [18] reported similar results using biosolid amendments. Composted materials were useful to abate GHG losses (lower GWP) without crop yield penalties. This was reflected in their yield-scaled $N_2O$ emissions, which were lower than for LO and NOLI (Figure 4). These did not increase enough to compensate for greater $N_2O$ losses. Applying DMPP in LI-2 decreased N2O emissions compared to the control and led to higher N uptake by the crop.

### *3.3. Dill Yield and Nutrient Content*

The fresh biomass production values of the aerial part of the dill plants with different fertilizer scenarios show significant variation. The FERTI treatment had the greatest biomass production, with 28.9 Mg ha$^{-1}$. The stabilized organic treatments (HP, HP-2, VT, and LO) were second, producing slightly less than the FERTI treatment, with 25.8 Mg ha$^{-1}$, 26.3 Mg ha$^{-1}$, 26.2 Mg ha$^{-1}$, and 25.6 Mg ha$^{-1}$, respectively The treatments that obtained the worst agronomic results were EST and the treatment without fertilization (B), both with productions of 20.6 Mg ha$^{-1}$ (Table 5).

In addition to yield, it is essential to know the nutritional content of the biomass. Nitrate content is considered one of the most important elements of vegetable quality. Both environmental and agrotechnical factors influence $NO_3^-$-N concentrations in plants. Typically, leafy green vegetables accumulate $NO_3^-$-N, with concentrations reaching up to 6000 mg kg$^{-1}$. Dill is a vegetable with medium $NO_3^-$-N content. Significant differences were found in nitrate contents depending on the treatments applied (Table 5). No differences were observed between the fresh and stabilized organic treatments and the control treatment.

**Table 4.** Estimated cumulative fluxes during the 55-day measuring period.

| Treatment | $CH_4$ (mg m$^{-2}$) | $N_2O$ (mg m$^{-2}$) | $CO_2$ (mg m$^{-2}$) | $CO_2$eq (kg ha$^{-1}$) |
|---|---|---|---|---|
| B | −12.07 a | 9 a | 27,740 bc | 20 a |
| HP | −6.53 ab | 12 ab | 28,671 cd | 30 ab |
| HP-2 | −6.33 ab | 13 ab | 31,072 de | 33 ab |
| VT | 6.23 c | 13 ab | 34,868 f | 36 ab |
| LO | 16.07 d | 181 d | 38,236 g | 485 d |
| EST | −0.30 bc | 10 ab | 32,590 ef | 29 ab |
| NOLI | −8.00 ab | 31 c | 26,551 bc | 82 c |
| LI-2 | −10.67 a | 18 b | 24,851 b | 47 b |
| FERTI | −4.07 ab | 8 a | 19,518 a | 20 a |
| SEM | 3.2 | 3 | 1073 | 9 |
| *F-anova* | 7.7 *** | 327 *** | 27 *** | 303 *** |

$CO_2$eq: $CO_2$eq equivalent added $C0_2$, $N_2O$, and $CH_4$ emissions with the corresponding GWP; SEM: standard error of the mean. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. *** Significant difference between treatments at $p < 0.001$. Treatments with different letters within the same column represent significant differences ($p < 0.05$) tested separately for each gas.

**Table 5.** Dill yield according to treatment.

| Treatment | Fresh Weight Basis | Dry Weight Basis | $NO_3^-$-N |
|---|---|---|---|
| | (Mg ha$^{-1}$) | | (mg kg$^{-1}$) |
| **B** | 20.6 a | 3.6 a | 829b |
| **HP** | 25.8 bc | 4.5 bcd | 703 b |
| **HP-2** | 26.3 bc | 4.6 cd | 505 ab |
| **VT** | 26.2 bc | 4.7 d | 469 ab |
| **LO** | 25.6 bc | 4.4 bcd | 650 ab |
| **EST** | 20.6 a | 3.6 a | 201 a |
| **NOLI** | 22.1 ab | 3.9 ab | 1373 c |
| **LI-2** | 22.4 ab | 3.9 ab | 5387 e |
| **FERTI** | 28.9 c | 4.6 d | 2896 d |
| *F-anova* | *11.5 **** | *10.28 **** | *109 **** |

N-$NO_3^-$: expressed on a dry matter basis. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. *** Significant difference between treatments at $p < 0.001$. Different letters within a column indicate significant differences between treatments ($p < 0.05$).

In terms of the macronutrient compounds extracted from the dill biomass, a low absorption N-rate of fresh organic fertilizers was observed (Table 6). Most of the N in these treatments is organic and must be mineralized to be assimilated by the plants. Stabilized organic and inorganic treatments (NOLI and FERTI) showed similar behavior and were less efficient than the LI-2 treatment. The NUE values reported significant differences, with the highest efficiency for LI-2 (30%) and the lowest for LO (2%).

**Table 6.** N, P, K extraction by dill, according to treatment.

| Treatment | N | P | K | NUE | PUE | KUE |
|---|---|---|---|---|---|---|
| | | (kg ha$^{-1}$) | | | % index | |
| B | 79 a | 5.89 a | 25.5 a | - | - | - |
| HP | 116 cde | 8.09 d | 35.3 d | 23 bc | 19 a | 1.67 ab |
| HP-2 | 104 bcd | 8.03 cd | 35.9 de | 15 b | 40 a | 0.67 a |
| VT | 95 ab | 8.24 d | 35.7 de | 13 ab | 12 a | 1.00 a |
| LO | 104 bcd | 6.69 ab | 26.9 ab | 15 b | 53 ab | 6.33 c |
| EST | 83 a | 7.19 bcd | 35.1 d | 2 a | 12 a | 0.33 a |
| NOLI | 101 bc | 6.87 abc | 30.7 bc | 14 b | 61 ab | 3.00 b |
| LI-2 | 127 e | 7.86 cd | 32.9 cd | 30 c | 219 c | 6.00 c |
| FERTI | 119 de | 6.39 ab | 39.2 e | 25 bc | 183 bc | 25.67 d |
| *F-anova* | *6.67 **** | *4.55 *** | *11.18 **** | *5.18 *** | *3.13 ** | *223.08 **** |

NUE/PUE/KUE: nitrogen/phosphorus/potassium use efficiency. HP: wastewater treatment biosolid + *Phoenix dactilifera* leaf prunings; HP-2: agrifood sludge from pear processing wastewater + *Phoenix dactilifera* leaf prunings; VT: vermicompost cow manure; LO: biosolid; EST: cow manure; NOLI: NPK inorganic fertilizer; LI-2: NPK + DMPP inorganic fertilizer; FERTI: fertigation. *, ** and *** Significant difference between treatments at $p$-value 0.01, 0.001, and <0.0001, respectively. Different letters within a column indicate significant differences between treatments ($p < 0.05$).

The dill plants that performed the best in P extraction were those fertilized with VT and compost. In general, dill plants with stabilized organic fertilizers showed higher N, P, and K content than the inorganic treatments. The worst P extraction performance was with the FERTI treatment, which may be due to the fact that less P was supplied because, in each fertigation, N could be dosed independently. Concerning the biomass levels of K extraction, we can observe significant differences between treatments following the same tendency as P with lower extraction levels. The efficiency indicators PUE and KUE showed the same trend: with EST, there is very low efficiency compared to the other treatments.

## 4. Discussion

### *4.1. Effect of Fertilization Treatments on Soil Properties*

At the end of the experiment (day 55), the pH of the soil had decreased compared to the beginning of the experiment with the different treatments. This was more extreme in the NOLI, LI-2, and EST treatments, probably due to the more intense action of nitrifying bacteria that can consume alkalinity through their metabolic pathway, as has been demonstrated in other studies [10,37]. The soil with the compost treatment (HP) was the only one that increased its value at the end of the growing cycle, ending the experiment with a pH very similar to the control (7.99). An increase in undesirable ions is one of the main constraints of organic fertilizers. Scotti et al. [38] explain the increase in soil salinity due to the effects of direct ion solubilization and the release of soluble mineral nutrients with compost mineralization [39,40]. At the end of the experiment, the soil EC value of the different treatments increased, especially in the NOLI treatment, probably due to overfertilization.

In general, applying organic amendments increases soil Pe content [18,41], coinciding with the results obtained in this experiment. The bio-stabilized organic treatments showed the most variation for NT with respect to the control treatment. The inorganic treatments and the fresh organic treatments also increased soil TN, but the increase was significantly lower. These differences found at the beginning of the trial may be due to the higher organic N supply from the compost [42]. One of the limitations of using compost as a fertilizer is the uncertainty about the amount of nutrients available to the plant, especially N and P, due to the presence of both inorganic and organic matter [43]. At the end of the experiment (day 55), all the treatments had reduced soil TN content, except fertigation, although all had significantly higher values than the control. By analyzing the bio-stabilized organic treatments, the reduction in TN shows how these organic fertilizers were able to slowly release inorganic N in combination with the nutritional needs of the crop [12], despite dill being a winter and short-cycle crop.

In relation to N-$NO_3^-$ dynamics, the results coincide with those Wang et al. [44] found in winter crop fertilization trials in different soils under the same soil and climatic conditions. They detected more intense nitrification in soils with moisture conditions alternating between saturation and unsaturation than in permanently saturated soils or in soils with long periods of drought. These variable conditions between saturation–unsaturation have been observed in the soil under study due to the drip irrigation method. However, in the LI-2 treatment, we can observe a very slight $NH_4^+$-N variation between the beginning and the end of the experiment, despite the fact that this material also provided a large amount of $NH_4^+$-N. This could be because the DMPP nitrification inhibiting actor slowed down the enzymes responsible for the first step of nitrification. The effectiveness of DMPP in irrigated soils is influenced by the soil texture [45], pH [46], or even SOC [47], which, if found in very labile forms, can promote denitrification processes given the heterotrophic nature of the bacteria responsible for this process [48]. Finally, the FERTI treatment showed the greatest increase in $NO_3^-$-N concentrations, which is evidence of N over-fertilization. This excess of $NO_3^-$-N in the soil after crop harvesting can lead to leaching and even groundwater contamination [49].

An increase in SOC was observed due to the different stimulation of the soil microbiota as a consequence of adding OM [50]. The VT treatment, which had the highest value at the beginning of the experiment, was the only organic treatment that did not increase its SOC value at the end of the experiment, possibly due to its labile condition and particle size, which favors intense OM mineralization in amended soil.

### *4.2. Effect of Fertilization Treatments on GHG Emissions*

We can observe that high $CO_2$ emissions indicate high soil activity, correlated with labile C content [51]: fresh organic fertilizers > stabilized organic fertilizers > inorganic fertilizers. These results have been observed in other works on the application of organic amendments to soil. De la Fuente et al. [52] detected an increase in $CO_2$ emissions after applying organic amendments to clay loam soil. Subsequently, from day 30 of the trial, all the treatments gradually increased $CO_2$ emissions until the end of the trial, which could be due to the respiration and gas exchange of the dill plants' root systems.

Comparing the results obtained in the treatments with inorganic fertilization, we can see that in the case of the FERTI treatment, the emission values were the lowest of all those in the experiment because this treatment did not provide N-$NH_4^+$. With NOLI and LI-2, which contributed a proportion of N-$NH_4^+$, the emissions were higher in the plots treated with NOLI. This could be a consequence of the nitrification inhibitor substances (DMPP) in the LI-2 fertilizer, since these substances have been shown to be effective in mitigating $N_2O$ emissions in soil. According to Huérfano et al. [53], between 30 and 50% of $N_2O$ emissions can be mitigated by using nitrification inhibiting fertilizers.

This sink effect was caused by the creation of methanotrophic process conditions. Under aerobic conditions, methane is converted into $CO_2$ by the enzymatic activity of aerobic methanotrophic bacteria that use methane as a source of C and energy for their growth [54]. Similar results were observed by Liu et al. [55] in a study on $CH_4$ emissions in agro-pastoral soils, where they also detected higher $CH_4$ production in soil after applying fresh organic fertilizers. The treatments with a significantly higher sink effect were LI-2 and the control plot ($-0.11$ and $-0.12$ kg C-$CH_4$ $ha^{-1}$, respectively). This $CH_4$ sink effect has been reported in other works on soils from Mediterranean environments [56,57]. In agricultural soils, it has been related to several factors: (1) soil type [58,59], which influences the drainage and porosity of the soil; (2) N fertilization rates [60], as other bacteria involved in the N cycle can compete with methanotrophic bacteria for oxygen; (3) the type of irrigation [61], with flood-type irrigation leading to greater soil saturation and the formation of anaerobic microsites; (4) or soil temperature [55], as there is a direct relationship between increased temperatures and $CH_4$ production.

The IPCC [62] provides a methodological guide for GHG emission inventories. It proposes a default $N_2O$ emission factor (EF $N_2O$) of 1% TN for irrigated crops in Mediterranean climate areas. Other works on horticulture in Mediterranean environments have reported that the 1% emission factor the IPCC advises by default overestimates the emissions of this gas in Mediterranean areas [17,63]. These studies seem to agree with the emission ratios measured in this work (VT 0.15%, HP 0.14%, HP-2 0.14%, NOLI 0.34%, LI-2 0.20%), which indicate that N2O emissions are not directly related to the amount of nitrogen applied [64] but to other factors, such as management methodology [65], the irrigation system [17], or the forms of nitrogen applied, which depend on the nature of the fertilizing material.

### 4.3. Effect of Fertilization Treatments on Dill Yield and Nutrient Content

Comparing the yield between the different fertilizing scenarios (stabilized organic fertilizers, fresh organic fertilizers, and inorganic fertilizers), the bio-stabilized organic treatments obtained significantly higher production than the inorganic treatments. This includes fertilizers with nitrification inhibitors, LI-2, and the conventional treatment (NOLI), with the production of 22.4 Mg $ha^{-1}$ and 22.1 Mg $ha^{-1}$, respectively. The low performance of the manure treatment could have been due to: (1) NPK content that was not balanced to the nutritional needs of dill, causing a deficiency in some of these elements, (2) the freshness of the material, making homogeneous application difficult, or (3) a phytotoxic effect on dill seed germination. The high content of $NH_4^+$-N present in this type of livestock waste [66] has been shown to have a negative effect on germination and the early stages of herbaceous plants. El-Zaeddi et al. [67] obtained a somewhat lower average production (22.5 Mg $ha^{-1}$) than that obtained in this study (24.3 Mg $ha^{-1}$) in their field study on dill production.

The treatment with the highest dry matter content with a yield of 4.7 t $ha^{-1}$ was VT, similar to the report by Fjelkner-Modig et al. [68], who found a higher dry weight yield in a dill crop with organic fertilization. As with the fresh biomass yield, the lowest results were found for the crop without fertilization (B) and EST, with 3.6 t $ha^{-1}$.

Acceptable daily nitrate intake is 3.7 mg $kg^{-1}$-body weight [69]. Herbs such as dill are consumed in small quantities, so their daily intake is not comparable to leafy vegetables. On average, the nitrate contents obtained in this trial were similar to those found by other authors [70] for dill crops. The inorganic treatments (NOLI, LI-2, and FERTI) showed the highest nitrate content, which differs from De Martin and Restani [71], who found significantly higher $NO_3^-$-N content in organically fertilized crops than in those conventionally produced.

The low mineralization rate of fresh fertilizers after short-term application to the soil [72] could have caused the low N extraction efficiency of the EST treatment. This low yield could be caused by the loss of nitrates through leaching [37] and denitrification [72]. The use of DMPP produced a two-fold increase in NUE [18]. In general, NUE values reported low values of efficiency compared to the average values obtained by other authors [73]. The inorganic P applied in the FERTI, LI-2, and NOLI treatments could have been partly immobilized by limestone in the soil, forming insoluble calcium phosphates [74]. The organic forms in the organic fertilizers could have avoided or slowed down this precipitation/insolubilization.

## 5. Conclusions

Applying the proposed bio-stabilized organic amendments to irrigated dill cropping was an efficient management strategy to preserve the sustainability of intensive horticultural cropping systems in the Mediterranean area. Comparing organic and inorganic-based fertilizing scenarios has provided useful results to optimize the commercial production of aromatic plants without yield or environmental penalties.

In addition to achieving yields comparable to those obtained using inorganic fertilizers, the organic amendments have a positive effect on maintaining and restoring soil carbon, with the expected consequences of soil sustainability. Directly applying fresh organic amendments has been shown to be a less recommendable option (less yield, more

GHG emissions, lower nutrient indexes) than using bio-stabilized organic fertilizers. In this particular study, the limitations of the experiment included the sampling frequency. Likewise, a longer sampling period of soil and GHGs (pre-planting and post-harvest) would also have been useful to relate to the data obtained.

Inorganic advanced slow-release fertilizers, which are increasingly being used in intensive scenarios, are agronomically efficient and also have low GHG emissions. However, with long-term repeated use, a loss of organic fertility, C sinks, and, especially, poor soil properties can be expected, with overall losses in sustainability and problems adapting to climate change. To corroborate this, experiments in long-term trials are recommended for this type of study, relating the effects of treatments and climatic events.

**Author Contributions:** Conceptualization, R.M. and M.D.P.-M.; methodology, F.J.A.-R.; software, L.O.; validation, E.A., J.M.-T., J.S.-T. and E.M.-S.; formal analysis, E.M.-S. and J.S.-T.; investigation, E.M.-S., J.S.-T., F.J.A.-R. and E.A.; resources M.D.P.-M.; data curation, M.D.P.-M.; writing—original draft preparation, L.O.; writing—review and editing, M.Á.B.; visualization, J.M.-T.; supervision, M.Á.B. and J.M.-T.; project administration, R.M.; funding acquisition, R.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Ministry of Economy and Competitiveness of Spain and by ERDF A way of making Europe: Project AGL2013-41612-R and Grant EQC2018-004170-P funded by MCIN/AEI/10.13039/501100011033.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank SME Hermanos Lucas for sharing its production fields for this experiment.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Jana, S.; Shekhawat, G.S. *Anethum graveolens*: An Indian traditional medicinal herb and spice. *Pharmacogn. Rev.* **2010**, *4*, 179–184.
2. Bailer, J.; Aichinger, T.; Hackl, G.; Hueber, K.D.; Dachler, M. Essential oil content and composition in commercially available dill cultivars in comparison to caraway. *Ind. Crops Prod.* **2001**, *14*, 229–239. [CrossRef]
3. Cano Ortiz, A.; Martínez Lombardo, M.C. Plantas medicinales con alcaloides en la provincia de Jaén. *Boletín Del Inst. De Estud. Giennenses* **2009**, *200*, 125–163.
4. Carrubba, A. Sustainable Fertilization in Medicinal and Aromatic Plants. In *Medicinal and Aromatic Plants of the World*; Máthé, Á., Ed.; Springer: Berlin/Heidelberg, Germany, 2015; Volume 1.
5. Ferreira, C.S.S.; Seifollahi-Aghmiuni, S.; Destouni, G.; Ghajarnia, N.; Kalantari, Z. Soil degradation in the European Mediterranean region: Processes, status and consequences. *Sci. Tot. Environ.* **2022**, *805*, 150106. [CrossRef] [PubMed]
6. Lal, R. Anthropogenic influences on world soils and implications to global food security. *Adv. Agron.* **2007**, *93*, 69–93.
7. Robertson, G.; Paul, E.; Harwood, R. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science* **2000**, *80*, 1922–1925. [CrossRef] [PubMed]
8. Ashagrie, Y.; Zech, W.; Guggenberger, G.; Mamo, T. Soil aggregation, and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. *Soil Till. Res.* **2007**, *94*, 101–108. [CrossRef]
9. Pardo, G.; del Prado, A.; Martínez-Mena, M.; Bustamante, M.A.; Rodríguez Martín, J.A.; Alvaro-Fuentes, J.; Moral, R. Intensive orchard and horticulture systems in Spanish Mediterranean coastal areas: Is there a real possibility to contribute to C sequestration? *Agric. Ecosyst. Environ.* **2017**, *238*, 153–167. [CrossRef]
10. Marín-Martínez, A.; Sanz-Cobeña, A.; Bustamante, M.A.; Agulló, E.; Paredes, C. Effect of Organic Amendment Addition on Soil Properties, Greenhouse Gas Emissions and Grape Yield in Semi-Arid Vineyard Agroecosystems. *Agronomy* **2021**, *11*, 1477. [CrossRef]
11. Latini, A.; Giagnacovo, G.; Campiotti, C.A.; Bibbiani, C.; Mariani, S. A Narrative Review of the Facts and Perspectives on Agricultural Fertilization in Europe, with a Focus on Italy. *Horticulturae* **2021**, *7*, 158. [CrossRef]
12. Orden, L.; Iocoli, G.A.; Bustamante, M.Á.; Moral, R.; Rodríguez, R.A. Nutrient Release Dynamics in Argentinean Pampean Soils Amended with Composts under Laboratory Conditions. *Agronomy* **2022**, *12*, 795. [CrossRef]
13. Razza, F.; D'Avino, L.; L'Abate, G.; Lazzeri, L. The role of compost in bio-waste management and circular economy. In *Designing Sustainable Technologies, Products and Policies*; Benetto, E., Gericke, K., Guiton, M., Eds.; Springer: Cham, Switzerland, 2018; pp. 133–143.
14. Sanz-Cobena, A.; García-Marco, S.; Quemada, M.; Gabriel, J.L.; Almendros, P.; Vallejo, A. Do cover crops enhance $N_2O$, $CO_2$ or $CH_4$ emissions from soil in Mediterranean arable systems? *Sci. Total Environ.* **2014**, *466–467*, 164–174. [CrossRef] [PubMed]

15. Sanz-Cobena, A.; Lassaletta, L.; Aguilera, E.; del Prado, A.; Garnier, J.; Billen, G.; Iglesias, A.; Sánchez, B.; Guardia, G.; Abalos, D.; et al. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agric. Ecosyst. Environ.* **2017**, *238*, 5–24. [CrossRef]
16. Lombardi, B.; Orden, L.; Varela, P.; Garay, M.; Iocoli, G.A.; Montenegro, A.; Sáez-Tovar, J.; Bustamante, M.Á.; Juliarena, M.P.; Moral, R. Is Dairy Effluent an Alternative for Maize Crop Fertigation in Semiarid Regions? An Approach to Agronomic and Environmental Effects. *Animals* **2022**, *12*, 2025. [CrossRef] [PubMed]
17. Cayuela, M.L.; Aguilera, E.; Sanz-Cobena, A.; Adams, D.C.; Abalos, D.; Barton, L.; Ryalsh, R.; Silver, W.L.; Alfaro, M.A.; Pappa, V.A.; et al. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. *Agric. Ecosyst. Environ.* **2017**, *238*, 25–35. [CrossRef]
18. Vico, A.; Sáez, J.A.; Pérez-Murcia, M.D.; Martinez-Tomé, J.; Andreu-Rodríguez, J.; Agulló, E.; Bustamante, M.A.; Sanz-Cobena, A.; Moral, R. Production of spinach in intensive Mediterranean horticultural systems can be sustained by organic-based fertilizers without yield penalties and with low environmental impacts. *Agric. Syst.* **2020**, *178*, 102765. [CrossRef]
19. IUSS Working Group WRB. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. In *World Soil Resources Reports Nr. 106*; FAO: Rome, Italy, 2015.
20. Ayers, R.S.; Westcot, D.W. Water quality for agriculture. In *FAO Irrigation and Drainage Paper*; 29 Rev 1; FAO: Rome, Italy, 1994.
21. Paredes, C.; Pérez-Murcia, M.D.; Pérez-Espinosa, A.; Bustamante, M.A.; Moreno-Caselles, J. Recycling of two-phase olive-mill cake "Alperujo" by co-composting with animal manures. *Commun. Soil Sci. Plant Anal.* **2015**, *46*, 238–247. [CrossRef]
22. Bustamante, M.A.; Paredes, C.; Moral, R.; Moreno-Caselles, J.; Perez-Murcia, M.D.; Perez- Espinosa, A.; Bernal, M.P. Co-composting of distillery and winery wastes with sewage sludge. *Water Sci. Technol.* **2007**, *56*, 187–192. [CrossRef] [PubMed]
23. Yeomans, J.; Bremner, J.M. A rapid and precise method for routine determination of organic carbon in soil. *Commun. Soil Sci. Plant Anal.* **1989**, *19*, 1467–1476. [CrossRef]
24. Olsen, S.; Cole, C.; Watanabe, F.; Dean, L. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. In *USDA Circular Nr 939*; US Gov. Print. Office: Washington, DC, USA, 1954.
25. Kabata-Pendias, A. *Trace Elements in Soils and Plants*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2010; p. 548.
26. Iammarino, M.; Di Taranto, A.; Cristino, M. Monitoring of nitrites and nitrates levels in leafy vegetables (spinach and lettuce): A contribution to risk assessment. *J. Sci. Food Agric.* **2014**, *94*, 773–778. [CrossRef]
27. López-Bellido, L.; López-Bellido, J.; Redondo, R. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. *Field Crop Res.* **2005**, *94*, 86–97. [CrossRef]
28. Sanz-Cobena, A.; Sanchez-Martin, L.; Garcia-Torres, L.; Vallejo, A. Gaseous emissions of $N_2O$ and NO and $NO_3{}^-$ leaching from urea applied with urease and nitrification inhibitors to a maize (Zea mays) crop. *Agric. Ecosyst. Environ.* **2012**, *149*, 64–73. [CrossRef]
29. Arias-Navarro, C.; Díaz-Pinés, E.; Kiese, R.; Rosenstock, T.S.; Rufino, M.C.; Stern, D.; Neufeldt, H.; Verchot, L.V.; Butterbach, K. Gas pooling: A sampling technique to overcome spatial heterogeneity of soil carbón dioxide and nitrous oxide fluxes. *Soil Biol. Biochem.* **2013**, *67*, 20–23. [CrossRef]
30. Sanz-Cobena, A.; Lassaletta, L.; Estellés, F.; Prado, A.D.; Guardia, G.; Abalos, D.; Aguilera, E.; Pardo, G.; Vallejo, A.; Sutton, M.A.; et al. Yieldscaled mitigation of ammonia emission from N fertilization: The Spanish case. *Environ. Res. Lett.* **2014**, *9*, 125005. [CrossRef]
31. Guardia, G.; Cangani, M.T.; Andreu, G.; Sanz-Cobena, A.; García-Marco, S.; Álvarez, J.M.; Recio-Huetos, J.; Vallejo, A. Effect of inhibitors and fertigation strategies on GHG emissions, NO fluxes and yield in irrigated maize. *Field Crop Res.* **2017**, *204*, 135–145. [CrossRef]
32. Menéndez, S.; Merino, P.; Pinto, M.; González-Murua, C.; Estavillo, J.M. 3,4-Dimethylpyrazol phosphate effect on nitrous oxide, nitric oxide, ammonia, and carbon dioxide emissions from grasslands. *J. Environ. Qual.* **2006**, *35*, 973–981. [CrossRef] [PubMed]
33. Aguilera, E.; Lassaletta, L.; Gattinger, A.; Gimeno, B.S. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *168*, 25–36. [CrossRef]
34. Van Groenigen, J.W.; Velthof, G.L.; Oenema, O.; van Groenigen, K.J.; van Kessel, C. Towards an agronomic assessment of $N_2O$ emissions: A case study on arable crops. *Eur. J. Soil Sci.* **2010**, *61*, 903–913. [CrossRef]
35. IPCC Chapter 7: The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2021; p. 132.
36. Di Rienzo, J.; Casanoves, F.; Balzarini, M.G.; Gonzalez, L.; Tablada, M.; Robledo, C.W. *InfoStat*; FCA Universidad Nacional de Córdoba: Córdoba, Argentina, 2020.
37. Sánchez-Monedero, M.A.; Roig, A.; Paredes, C.; Bernal, M.P. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC and maturity of the composting mixtures. *Bioresour. Technol.* **2001**, *78*, 301–308. [CrossRef]
38. Scotti, R.; Pane, C.; Spaccini, R.; Palese, A.M.; Piccolo, A.; Celano, G.; Zaccardelli, M. On-farm compost: A useful tool to improve soil quality under intensive farming systems. *Appl. Soil Ecol.* **2016**, *107*, 13–23. [CrossRef]
39. Chan, K.Y.; Dorahy, C.; Tyler, S. Determining the agronomic value of composts produced from garden organics from metropolitan areas of New South Wales, Australia. *Aust. J. Exp. Agric.* **2007**, *47*, 1377–1382. [CrossRef]

40. Bonanomi, G.; D'Ascoli, R.; Scotti, R.; Gaglione, S.; Gonzalez, M.; Sultana, S.; Scelza, R.; Rao, M.; Zoina, A. Soil quality recovery and crop yield enhancement by combined application of compost and wood to vegetables grown under plastic tunnels. *Agric. Ecosyst. Environ.* **2014**, *192*, 1–7. [CrossRef]
41. Orden, L.; Ferreiro, N.; Satti, P.; Navas-Gracia, L.M.; Chico-Santamarta, L.; Rodríguez, R.A. Effects of Onion Residue, Bovine Manure Compost and Compost Tea on Soils and on the Agroecological Production of Onions. *Agriculture* **2021**, *11*, 962. [CrossRef]
42. Iocoli, G.A.; Orden, L.; López, F.M.; Gómez, M.A.; Villamil, M.B.; Zabaloy, M.C. Towards Sustainable Dairy Production in Argentina: Evaluating Nutrient and $CO_2$ Release from Raw and Processed Farm Waste. *Agronomy* **2021**, *11*, 2595. [CrossRef]
43. Bernal, M.P.; Sommer, S.G.; Chadwick, D.; Qing, C.; Guoxue, L.; Michel, F.C. Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits. *Adv. Agron.* **2017**, *144*, 143–233.
44. Wang, Y.S.; Xue, M.; Zheng, X.H.; Ji, B.M.; Du, R.; Wang, Y.F. Effects of environmental factors on $N_2O$ emission from and $CH_4$ uptake by the typical grasslands in the Inner Mongolia. *Chemosphere* **2005**, *58*, 205–215. [CrossRef] [PubMed]
45. Barth, G.; von Tucher, S.; Schmidhalter, U. Effectiveness of 3,4-dimethylpyrazole phosphate as nitrification inhibitor in soil as influenced by nitrification inhibitor concentration, application form, and soil matric potential. *Pedosphere* **2008**, *18*, 378–385. [CrossRef]
46. Robinson, A.; Di, H.J.; Cameron, K.C.; Podolyan, A.; He, J. The effect of soil pH and dicyandiamide (DCD) on $N_2O$ emissions and ammonia oxidiser abundance in a stimulated grazed pasture soil. *J. Soils Sediments* **2014**, *14*, 1434–1444. [CrossRef]
47. Marsden, K.A.; Scowen, M.; Hill, P.W.; Jones, D.L.; Chadwick, D.R. Plant acquisition and metabolism of the synthetic nitrification inhibitor dicyandiamide and naturally-occurring guanidine from agricultural soils. *Plant Soil* **2015**, *395*, 201–214. [CrossRef]
48. Webb, J.; Pain, B.; Shabtai, B.; Morgan, J. The impact of manure application methods on emissions of ammonia, nitrous oxide and on crop response—A review. *Agric. Ecosyst. Environ.* **2010**, *137*, 39–46. [CrossRef]
49. Elmi, A.; Madani, A.; Gordon, R.; MacDonald, P.; Stratton, G.W. Nitrate nitrogen in the soil profile and drainage water as influenced by manure and mineral fertilizer application in a Barley–Carrot production system. *Water Air Soil Pollut.* **2005**, *160*, 119–132. [CrossRef]
50. Mondini, C.; Cayuela, M.L.; Sinicco, T.; Sánchez-Monedero, M.A.; Bertolone, E.; Bardi, L. Soil application of meat and bone meal. Short-term effects on mineralization dynamics and soil biochemical and microbiological properties. *Soil Biol. Biochem.* **2008**, *40*, 462–474. [CrossRef]
51. Bernal, M.P.; Paredes, C.; Sánchez-Monedero, M.A.; Cegarra, J. Maturity and stability parameters of composts prepared with a wide range of organic residues. *Bioresour. Technol.* **1998**, *63*, 91–99. [CrossRef]
52. de la Fuente, C.; Alburquerque, J.A.; Clemente, R.; Bernal, M.P. Soil C and N mineralisation and agricultural value of the products of an anaerobic digestion system. *Biol. Fertil. Soils* **2013**, *49*, 313–322. [CrossRef]
53. Huérfano, X.; Fuertes-Mendizábal, T.; Dunabeitia, M.K.; González-Murua, C.; Estavillo, J.M.; Menéndez, S. Splitting the application of 3,4-dimethylpyrazole phosphate (DMPP): Influence on greenhouse gases emissions and wheat yield and quality under humid Mediterranean conditions. *Eur. J. Agron.* **2015**, *64*, 47–57. [CrossRef]
54. Svetlana, N.D.; Dunfield, P.F. Chapter three—Facultative and Obligate Methanotrophs: How to Identify and Differentiate Them. In *Methods in Enzymology*; Rosenzweig, A.C., Ragsdale, S.W., Eds.; Academic Press: Cambridge, MA, USA, 2011; Volume 495, pp. 31–44.
55. Liu, J.; Chen, H.; Yang, X.; Gong, Y.; Zheng, X.; Fan, M.; Kuzyakov, Y. Annual methane uptake from different land uses in an agro-pastoral ecotone of northern China. *Agric. For. Meteorol.* **2017**, *236*, 67–77. [CrossRef]
56. Sanchez-Martin, L.; Sanz-Cobena, A.; Meijide, A.; Quemada, M.; Vallejo, A. The importance of the fallow period for $N_2O$ and $CH_4$ fluxes and nitrate leaching in a Mediterranean irrigated agroecosystem. *Eur. J. Soil Sci.* **2010**, *61*, 710–720. [CrossRef]
57. Meijide, A.; Gruening, C.; Goded, I.; Seufert, G.; Cescatti, A. Water management reduces greenhouse gas emissions in a Mediterranean rice paddy field. *Agric. Ecosyst. Environ.* **2017**, *238*, 168–178. [CrossRef]
58. Le Mer, J.; Roger, P. Production, Oxidation, Emission and Consumption of Methane by Soils: A Review. *Eur. J. Soil Biol* **2001**, *37*, 25–50. [CrossRef]
59. Tate, K.R. Soil methane oxidation and land-use change—From process to mitigation. *Soil Biol. Biochem.* **2015**, *80*, 260–272. [CrossRef]
60. van Kessel, C.; Venterea, R.; Six, J.; Adviento-Borbe, M.A.; Linquist, B.; van Groenigen, K.J. Climate, duration, and N placement determine $N_2O$ emissions in reduced tillage systems: A meta-analysis. *Glob. Chang. Biol.* **2013**, *19*, 33–44. [CrossRef] [PubMed]
61. Liang, K.M.; Zhong, X.H.; Huang, N.R.; Lampayan, R.M.; Pan, J.F.; Tian, K.; Liu, Y.Z. Grain yield, water productivity and $CH_4$ emission of irrigated rice in response to water management in south China Agric. *Water Manag.* **2016**, *163*, 319–331. [CrossRef]
62. IPCC Volume 4: Agriculture, Forestry and Other Land Use. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. (Eds.) IGES: Kamiyamaguchi Hayama, Japan, 2006; Volume 4, ISBN 4-88788-032-4.
63. Aguilera, E.; Lassaletta, L.; Sanz-Cobena, A.; Garnier, J.; Vallejo, A. The potential of organic fertilizers and water management to reduce $N_2O$ emissions in Mediterranean climate cropping systems. A review. *Agric. Ecosyst. Environ.* **2013**, *164*, 32–52. [CrossRef]
64. Philibert, A.; Loyce, C.; Makowski, D. Assessment of the quality of meta-analysis in agronomy. *Agric. Ecosyst. Environ.* **2012**, *148*, 72–82. [CrossRef]
65. Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H. Emissions of $N_2O$ and NO from fertilized fields: Summary of available measurement data. *Glob. Biogeochem. Cycles* **2002**, *16*, 1058. [CrossRef]

66. Birkmose, T.S. Nitrogen recovery from organic manures: Improved slurry application techniques and treatment; the Danish scenario. In Proceedings of the International Fertilizer Society 656, York, UK, 12 December 2009; p. 24.
67. El-Zaeddi, H.; Martínez-Tomé, J.; Calín-Sánchez, A.; Burló, F.; Carbonell-Barrachina, A. Irrigation dose and plant density affect the volatile composition and sensory quality of dill (*Anethum graveolens* L.). *J. Sci. Food Agric.* **2017**, *97*, 427–433. [CrossRef]
68. Fjelkner-Modig, S.; Bengtsson, H.; Nystrõm, S.; Stegmark, R. The Influence of Organic and Integrated Production on Nutritional, Sensory and Agricultural Aspects of Vegetable Raw Materials for Food Production. *Acta Agric. Scand. Sect. B Plant Soil Sci.* **2000**, *50*, 102–113. [CrossRef]
69. EFSA Panel on Contaminants in the Food Chain. Scientific Opinion on possible health risks for infants and young children from the presence of nitrates in leafy vegetables. *EFSA J.* **2010**, *8*, 1935.
70. Tamme, T.; Reinik, M.; Roasto, M.; Meremäe, K.; Kiis, A. Nitrate in leafy vegetables, culinary herbs, and cucumber grown under cover in Estonia: Content and intake. *Food Addit. Contam.* **2010**, *3*, 108–113. [CrossRef]
71. De Martin, S.; Restani, P. Determination of nitrates by a novel ion chromatographic method: Occurrence in leafy vegetables (organic and conventional) and exposure assessment for Italian consumers. *Food Addit. Contam.* **2003**, *20*, 787–792. [CrossRef] [PubMed]
72. Chadwick, D.; John, F.; Pain, B.; Chambers, B.; Williams, J. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: A laboratory experiment. *J. Agric. Sci.* **2000**, *134*, 159–168. [CrossRef]
73. Brentrup, F.; Pallière, C. Nitrogen Use Efficiency as an Agro-Environmental Indicator. In Proceedings of the OECD Workshop on OECD Agri-environmental Indicators: Lessons Learned and Future Directions, Leysin, Switzerland, 23–26 March 2010.
74. Mengel, K.; Kirkby, E.A. *Principles of Plant Nutrition*; Kluwer Academic Publishers: Dordrecht, Switzerland, 2001; p. 849.