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Project Report

Agronomic Evaluation of Biochar, Compost and Biochar-Blended Compost across Different Cropping Systems: Perspective from the European Project FERTIPLUS

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Abstract: This paper reports the results on the agronomic performance of organic amendments in the EU 7th FP project "FERTIPLUS—reducing mineral fertilizers and agro-chemicals by recycling treated organic waste as compost and bio-char". Four case studies on field-scale application of biochar, compost and biochar-blended compost were established and studied for three consecutive years in four distinct cropping systems and under different agro-climatic conditions in Europe. These included the following sites: olive groves in Murcia (Spain), greenhouse grown tomatoes in Almeria (Spain), an arable crop rotation in Oost-Vlaanderen (Merelbeke, Belgium), and three vineyards in Friuli Venezia Giulia (Italy). A slow pyrolysis oak biochar was applied, either alone or in combination with organic residues: compost from olive wastes in Murcia (Spain), sheep manure in Almeria (Spain), and compost from biowaste and green waste in Belgium and Italy. The agronomical benefits were evaluated based on different aspects of soil fertility (soil total organic carbon (TOC), pH, nutrient cycling and microbial activity) and crop nutritional status and productivity. All amendments were effective in increasing soil organic C in all the field trials. On average, the increase with respect to the control was about 11% for compost, 20% for biochar-blended compost, and 36% for biochar. The amendments also raised the pH by 0.15–0.50 units in acidic soils. Only biochar had a negligible fertilization effect. On the contrary, compost and biochar-blended compost were effective in enhancing soil fertility by increasing nutrient cycling (25% mean increase in extractable organic C and 44% increase in extractable N), element availability (26% increase in available K), and soil microbial activity (26% increase in soil respiration and 2–4 fold enhancement of denitrifying activity). In general, the tested amendments did not show any negative effect on crop yield and quality. Furthermore, in vineyards and greenhouse grown tomatoes cropping systems, compost and biochar-blended compost were also effective in enhancing key crop quality parameters (9% increase in grape must acidity and 16% increase in weight, 9% increase in diameter and 8% increase in hardness of tomato fruits) important for the quality and marketability of the crops. The overall results of the project suggest that the application of a mixture of biochar and compost can benefit crops. Therefore, biochar-blended compost can support and maintain soil fertility.

Keywords: fertilization; nutrient recycling; organic waste management; pyrolysis; composting; soil organic matter; soil fertility; crop yield

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1. Introduction

A large amount and significant variety of organic wastes are produced within the European Union (EU). These include agricultural, yard and forestry wastes, sludges from water treatment plants, food processing residues, and an organic fraction in municipal waste. Such residues not only pose major concerns and costs regarding their disposal, but are at the moment not utilized to their full potential as a source of carbon and nutrients. Their application to soils could contribute to offset and restore the decrease in soil organic matter (SOM) and the disruption of nutrients cycling caused by the intensification of agricultural practices [1]. Hence, by returning nutrients to the soil, organic residues represent an important strategy to enhance environmental performance and support the sustainability of agricultural production systems [2].

The EU FP7 project FERTIPLUS aimed to identify innovative organic waste treatment technologies to recycle urban and agricultural wastes into valuable and safe products for use in agriculture. In particular, FERTIPLUS focused on the production and agricultural application of biochar, compost, and a mixture of both materials (biochar-blended compost) to evaluate their potential for closing the cycle of nutrients in different agro-climatic regions across Europe. The recycling of organic residues in agriculture, such as the use of organic and waste-based fertilisers and soil conditioners, is a strategy that builds on the EU Circular Economy Action Plan [3].

The first step of FERTIPLUS was to assess the amount and quality of organic waste available within the EU to identify and map their potential for recycling C and nutrients to soil and plant as either biochar or compost [4]. Biochar is the product of the thermal decomposition of organic material under limited supply of O_2 and at relatively low temperature (<700 °C) with the purpose to be applied to the soil as amendment [5]. Several biochars were produced from a range of available feedstocks and diversity of pyrolysis conditions to study their properties and use as soil amendment to increase nutrient retention [6–8]. These biochars were tested in laboratory scale assays to evaluate their agronomical properties [9].

An innovative aspect of the FERTIPLUS project was the study of the interaction of biochar with compost and other organic amendments during processing and or in application of such blends. While the favorable agronomic properties of biochar and compost have been already highlighted by several reviews [10–12] and meta-analyses [13], the interaction of biochar and composts has only attracted attention in recent years [14,15]. The blend of biochar and compost could theoretically benefit from the combination of the long-lasting physical and chemical properties of biochar, such as stability, water and nutrient retention, habitat provision for soil microorganisms [16], and the supply of labile organic C and nutrients by compost.

Recent scientific developments have led to the investigation of whether biochar would enhance composting efficiency [17–19]. Composting is a microbial processing that requires favorable growing conditions for the microorganisms involved. The addition of biochar to a composting pile theoretically can modify key physicochemical parameters and provide a more suitable habitat for the microorganisms involved and promote microbial growth. These favorable environmental conditions lead to an enhanced microbial activity and organic matter formation. The changes experienced by the biochar surface during composting (biochar activation) also have benefits in terms of nutrient retention, avoiding losses through leaching or volatilization during composting. These changes may potentially improve the agronomic performance of biochar-enriched compost when used as a soil amendment [20].

Several authors have pointed to a synergistic effect of biochar with compost that can mediate the soil microbial process, affecting soil nutrient cycles [21], promoting C stabilization though the formation of organo-mineral complexes [22], improving plant growth by nitrate-capture in co-composted biochar [23] or forming a coating on the outer and inner surfaces of biochar particles that adds hydrophilicity, redox-active moieties, and additional mesoporosity, which enhances biochar water interactions and thus increases nutrient retention [24]. However, this effect has not been corroborated, as other authors have found neutral or antagonistic interactive effects on several plant traits from blends of biochar and compost [25]. Either way, we hypothesize that the utilization of biochar and compost blends represents a valid strategy to enhance nutrient recovery from waste and increase water content, nutrient use efficiency, C storage, and microbial activity in soils [26].

In the last stage, the FERTIPLUS project evaluated a set of field trials where biochar, compost and biochar-blended compost were applied with the aim to assess their impact on different aspects of soil fertility (total organic carbon-TOC, pH, nutrient cycling, and microbial activity) and crop yield and quality at the field scale, with an emphasis on the interactions of biochar and composts. Here, we present the results of our assessments of agronomical performance and feasibility of these innovative waste treatment technologies upon their application to a range of climate, soil and crop types.

2. Materials and Methods

2.1. Rationale behind Field Scale Experiments

Field scale experiments were designed to evaluate the agronomical potential of biochar and a mixture of biochar and compost in different agroecosystems around Europe. Biochar was compared to the traditional agricultural practices in each region, which mostly relied on the use of compost or manure as the main source of organic matter.

Four locations were selected to cover a wide range of cultivars and agro climatic conditions of relevance for vast areas of Europe (Table 1). The crops investigated included: olive orchards in Southern Spain, vineyards in Northern Italy, a rotation of cereals and vegetables in Belgium, and tomato as an example of intensive agriculture in greenhouses in Southern Spain.

Table 1. Description of the common methodological strategy used for the agronomical evaluation of biochar and compost applications at the four experimental sites across Europe.

	Murcia (Spain)	**Friuli-Venezia-Giulia (Italy)**	**Merelbeke (Belgium)**	**Almería (Spain)**
				
Cultivation	Olive orchards	Vineyards	Rotation (cereals, vegetables, Italian ryegrass)	Tomato intensive cultivation under greenhouse
Organic amendments	Oak biochar Olive mill waste compost Mixture 10:90	Oak biochar Biowaste + green waste compost Mixture 10:90	Oak biochar Biowaste + green waste compost Mixture 10:90	Oak biochar Sheep manure Mixtures 10:90; 20:80 and 40:60
Dose (dry weight)	20 t ha^{-1}	ca. 20–40 t ha^{-1} (10.9 t C ha^{-1})	ca. 20–40 t ha^{-1} (10.9 t C ha^{-1})	100 t ha^{-1}
Soil fertility parameters	Soil organic matter, microbial activity	Soil organic matter, nutrients, microbial activity	Soil organic matter, nutrients	Soil organic matter, nutrients
Crop yield and quality parameters	Yield and plant nutritional status	Yield and fruit quality	Yield and nutrient content	Yield and fruit quality

The experimental design involved the use of a common methodological strategy, which was slightly adapted to local agricultural practices and climatic conditions. This common strategy involved the use of the same biochar in all locations and a local source of organic matter as soil amendment, and comparable evaluation criteria for assessing soil and plant nutritional status and crop yield (Table 1).

2.2. Description of Biochar and Organic Amendments

The biochar used in all field experiments was produced by PROININSO (Málaga, Spain) from the pyrolysis of oak (650 °C pyrolysis temperature, 12–18 h residence time in kiln, 0% Oxygen content). The agronomical characterization of the biochar is shown in Table 2.

Table 2. Physicochemical properties of the biochar and organic amendments (compost, biochar-blended composts and manure) used in the field trials.

Parameter	Biochar	TPOMW [1] Compost	TPOMW Compost + Biochar	BGW [2] Compost	BGW Compost + Biochar	Sheep Manure
TOC (%)	76.5	35.8	39.9	30.2	29.5	35.5
N (%)	0.8	2.35	2.20	2.7	2.5	1.5
C/N	95.6	15.2	18.2	11.2	11.8	23.7
pH	9.3	8.7	8.8	8.9	8.9	9.18
P (%)	0.19	1.45	1.32	0.49	0.43	0.53
K (%)	0.6	1.75	1.64	2.19	2.02	0.62
N-NH_4^+ (mg kg^{-1})	3.2	189	170	271	210	280
EC [3] (µS cm^{-1})	450	2700	2475	2532	2335	nd

[1] TPOMW: Two-phase olive mill wastes; [2] BGW: Biowaste and green waste; [3] EC: Electrical conductivity.

The organic amendments were: (1) olive-mill waste compost used in Murcia (Spain), (2) biowaste and green waste compost used in Italy and Belgium, and (3) sheep manure used in Almeria (Spain). The description of the composts and manure is presented in Table 2.

Two-phase olive-mill waste (TPOMW) compost was prepared at the facilities of SAT 1870 Casa Pareja (Jumilla, Murcia, Spain) from a mixture of approximately 50% of olive mill waste, 25% of sheep manure, and 25% of olive pruning. This starting mixture was composted for 31 weeks in trapezoidal piles of 1.5 m high with a 2 × 3 m base in an outdoor composting plant using the windrow system. This compost corresponds to the original compost traditionally used by the farm for its fertilization program. The biochar-blended compost was prepared by mixing olive mill waste compost and oak biochar in a dry weight ratio of 90/10 before its application to the soil. A more detailed description of the composting process is reported by López-Cano et al. [27].

The biowaste and green waste (BGW) compost utilized in Italy and Belgium was produced at a commercial composting plant, ISA Isontina Ambiente s.r.l. (Moraro, Gorizia, Italy). A mixture of green waste and organic fraction of municipal solid waste was used as feedstock for the process. The organic fraction was collected separately according to a door-to-door waste collection scheme. Regular composting of the mixture of green waste and the organic fraction of municipal solid waste was the reference treatment in the trial. The bio-oxidative stage of the composting process was executed for 30 days in lanes with automated mechanical turning and forced aeration. After the bio-oxidative stage, the curing phase was performed in separated windrows for 60 days. For the preparation of the biochar-blended composts, a dry weight ratio of green waste and organic fraction of municipal solid waste/biochar of 90/10 was applied and composted, similar to the biowaste and green waste compost. A more detailed description of the composting process is reported by Vandecasteele et al. [17].

The sheep manure used in Almería (Spain) consisted of a semi-dried farmyard sheep manure produced by a local company, which was stored for several months in the open until its final use. Mixtures of semi-dried farmyard sheep manure and reference biochar at different ratios (100:0; 90:10; 80:20 and 60:40 on a dry matter basis) were prepared by mechanically mixing just before their application to the soil.

2.3. Case-Study Description

The site descriptions, samples, and analytical methods for the four field experiments are described below.

2.3.1. Olive Orchard in Murcia (Spain)

The experiment was carried out on a commercial organic olive crop within the farm "SAT Casa Pareja", located in Southeast Spain (38°23′ N; 1°22′ W). The area has a semi-arid Mediterranean climate. It has an annual rainfall of 250 mm, which is mainly during the autumn and spring months, although the year 2014 was particularly dry, with only 192 mm. The mean daily maximum temperature is 20.7 °C and mean daily minimum temperature is 11.5 °C.

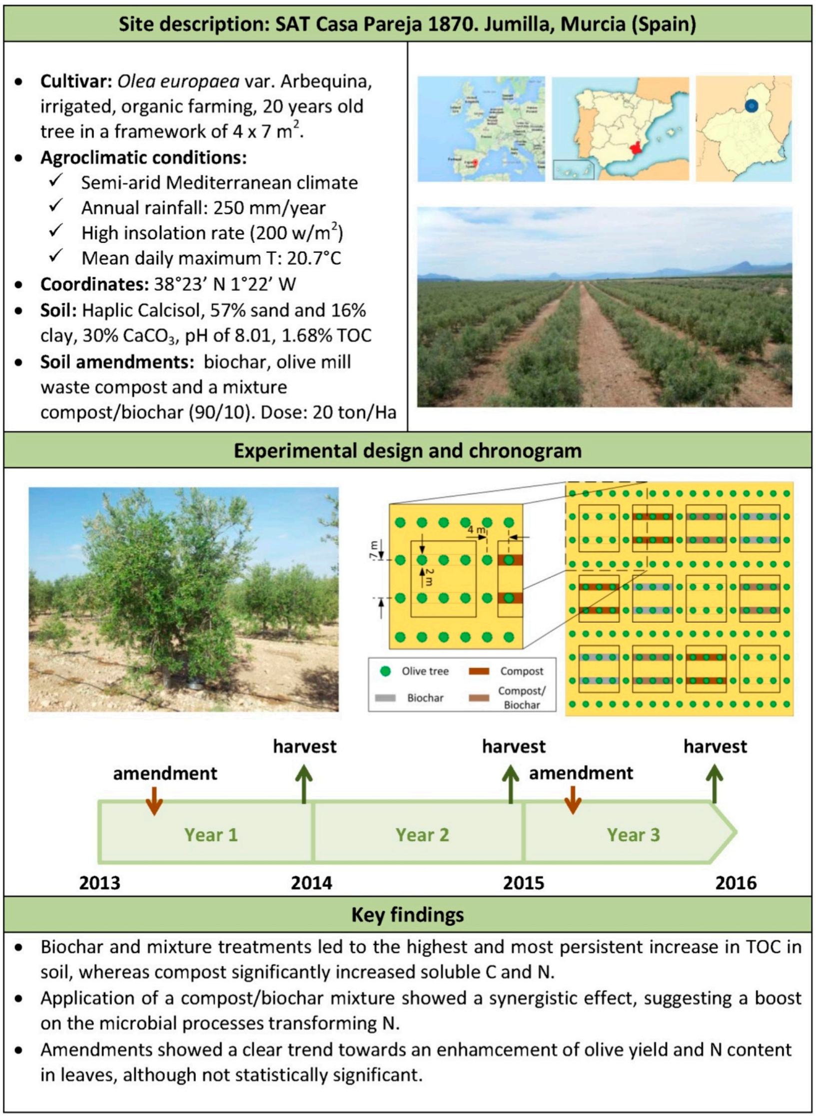
The soil at the experimental site is Haplic Calcisol with 57% sand and 16% clay, 30% $CaCO_3$ and a pH of 8.01. The concentration of total organic C (TOC) was 1.68%. Trial plots are planted with 20-year-old olive trees in a framework of 4×7 m^2.

Over the last 15 years, the olive orchard has been organically managed (EEC 834, 2007) and fertilization has exclusively consisted of compost application at 4 tons ha^{-1} (10 kg $tree^{-1}$) every second year. No mineral fertilizers, herbicides or pesticides have been applied.

Figure 1 shows the field trial layout with four treatments: (i) Control (no amendment) (ii) compost, (iii) biochar and (iv) a mixture of compost:biochar at 90:10 (dry weight), in a randomized block design with three replicates. Amendments were applied at 20 tons ha^{-1} along the irrigation pipelines. This corresponds to 16 kg $tree^{-1}$ or 6 tons ha^{-1} considering the whole plot area. Amendments were manually applied and immediately incorporated into the soil by ploughing at 15 cm.

The agronomical evaluation of soil quality was performed annually (in July) by studying TOC, total N (TN), extractable organic carbon (EOC), extractable nitrogen (EN) and NO_3^- in the top 25 cm soil. TOC and TN were determined in air dried samples by automatic elemental analysis (LECO CHNS-932, Saint Joseph, MI, USA) [28]. EOC, EN and NO_3^- were determined in the water extracts using a Photometer (Nanocolor 500 D MACHEREY-NAGEL, Germany) for EOC and EN and ion chromatography for NO_3^- (HPLC, model 861, Metrohm AG, Herisau, Switzerland) [29].

Crop yield was evaluated after three years of application by collecting and weighing the olives harvested from each olive tree in all treatments. The nutritional status of the olive crop was tested by foliar analysis as per Fernández-Escobar et al. [28]. Total concentrations of macro-, micro-nutrients were measured after HNO_3/H_2O_2 digestion by using inductively coupled plasma ICP-AES (ICAP 6500 DUO, Thermo Scientific, Waltham, MA, USA). Total N was determined by automatic elemental analysis (see above).



Site description: SAT Casa Pareja 1870. Jumilla, Murcia (Spain)

- **Cultivar:** *Olea europaea* var. Arbequina, irrigated, organic farming, 20 years old tree in a framework of 4 x 7 m^2.
- **Agroclimatic conditions:**
  - ✓ Semi-arid Mediterranean climate
  - ✓ Annual rainfall: 250 mm/year
  - ✓ High insolation rate (200 w/m^2)
  - ✓ Mean daily maximum T: 20.7°C
- **Coordinates:** 38°23′ N 1°22′ W
- **Soil:** Haplic Calcisol, 57% sand and 16% clay, 30% $CaCO_3$, pH of 8.01, 1.68% TOC
- **Soil amendments:** biochar, olive mill waste compost and a mixture compost/biochar (90/10). Dose: 20 ton/Ha

Experimental design and chronogram

Key findings

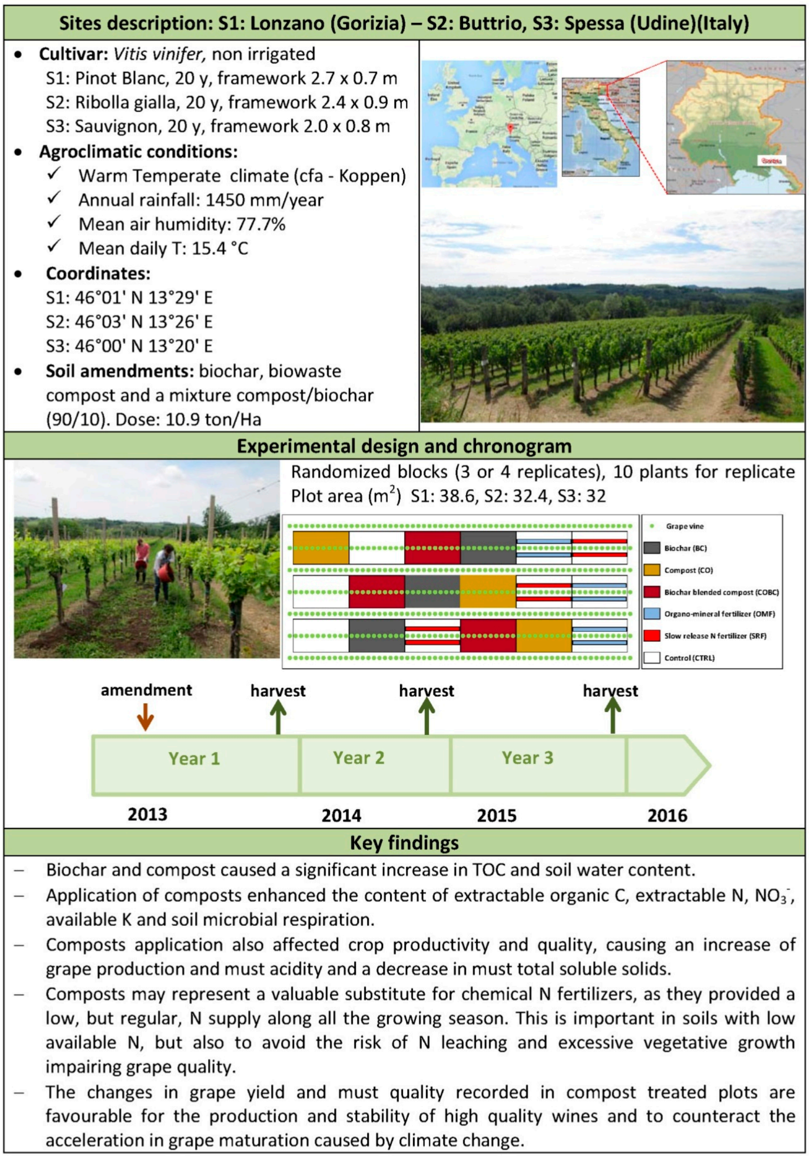
- Biochar and mixture treatments led to the highest and most persistent increase in TOC in soil, whereas compost significantly increased soluble C and N.
- Application of a compost/biochar mixture showed a synergistic effect, suggesting a boost on the microbial processes transforming N.
- Amendments showed a clear trend towards an enhamcement of olive yield and N content in leaves, although not statistically significant.

Figure 1. Description of the field scale experiment at Murcia (Spain): organic olive orchard.

2.3.2. Vineyards in Italy

The experiment was carried out in three different old vineyards (>20 years) located in Northeast Italy, characterized by soils with alkaline pH (8.0–8.1), silty clay loam/silty loam texture, 5.1–6.9% $CaCO_3$ and 1.1–2.1% TOC. Agroclimatic conditions were characterized by warm temperate climate, 1450 mm total annual rainfall, 15.4 °C mean daily temperature, and 77.7% mean air humidity.

The treatments performed in each site were: biochar (10.9 C ha^{-1}), biowaste and green waste compost (10.9 C ha^{-1}), biochar-blended compost, 10:90 w:w (10.9 C ha^{-1}), slow N release fertilizer (32.5 kg N ha^{-1}), organo-mineral fertilizer (32.5 kg N ha^{-1} common fertilization management in the area), control (no fertilization) (Figure 2). All fertilizers were distributed manually and incorporated about 25 cm from the strains on both sides of the row at the beginning of the growing season. Organic amendments were applied only in the first year of the trial, while organo-mineral and slow release fertilizers were applied each year.



Sites description: S1: Lonzano (Gorizia) – S2: Buttrio, S3: Spessa (Udine)(Italy)

- **Cultivar:** *Vitis vinifer,* non irrigated
  S1: Pinot Blanc, 20 y, framework 2.7 x 0.7 m
  S2: Ribolla gialla, 20 y, framework 2.4 x 0.9 m
  S3: Sauvignon, 20 y, framework 2.0 x 0.8 m
- **Agroclimatic conditions:**
  - ✓ Warm Temperate climate (cfa - Koppen)
  - ✓ Annual rainfall: 1450 mm/year
  - ✓ Mean air humidity: 77.7%
  - ✓ Mean daily T: 15.4 °C
- **Coordinates:**
  S1: 46°01' N 13°29' E
  S2: 46°03' N 13°26' E
  S3: 46°00' N 13°20' E
- **Soil amendments:** biochar, biowaste compost and a mixture compost/biochar (90/10). Dose: 10.9 ton/Ha

Experimental design and chronogram

Randomized blocks (3 or 4 replicates), 10 plants for replicate
Plot area (m^2) S1: 38.6, S2: 32.4, S3: 32

Key findings

- Biochar and compost caused a significant increase in TOC and soil water content.
- Application of composts enhanced the content of extractable organic C, extractable N, NO_3^-, available K and soil microbial respiration.
- Composts application also affected crop productivity and quality, causing an increase of grape production and must acidity and a decrease in must total soluble solids.
- Composts may represent a valuable substitute for chemical N fertilizers, as they provided a low, but regular, N supply along all the growing season. This is important in soils with low available N, but also to avoid the risk of N leaching and excessive vegetative growth impairing grape quality.
- The changes in grape yield and must quality recorded in compost treated plots are favourable for the production and stability of high quality wines and to counteract the acceleration in grape maturation caused by climate change.

Figure 2. Description of the field scale experiment in Italy: vineyards.

Each experimental plot was constituted by 10 vines for vineyard. The experimental design was a randomized complete block with three replications at Site 1 and 2 and four replicates at Site 3 (Figure 2).

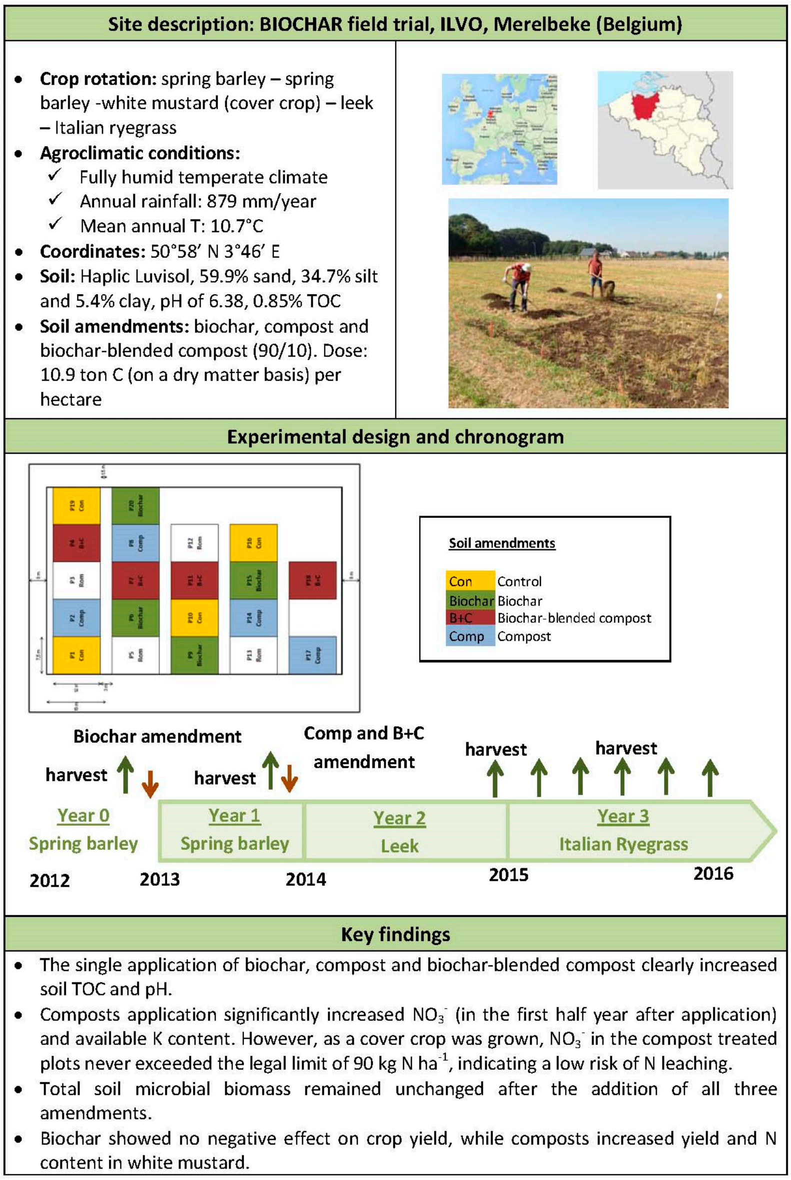
Soil samples (25 cm depth) from each plot of the trial were collected 5 times during every growing season, from bud break to maturation. Agronomical evaluation of soil was performed by analyzing water content, TOC, extractable organic C and N (EOC, EN) NO_3^- and available K. Water content and TOC were evaluated thermogravimetrically. EOC and EN were determined following extraction with K_2SO_4 0.5 M (1:4 w/v) using a TOC–TN analyzer. The content of NO_3^- was measured spectrophotometrically by reading the absorbance at 220 nm and subtracting the absorbance caused by organic matter at 275 nm [30]. Available K was determined by ICP after soil extraction with DTPA [31]. Dynamics of CO_2 emissions was measured every eight hours on moist samples (40% WHC equivalent to 50 g of dry soil) incubated for a month at 20 °C in the laboratory utilizing a GC (Agilent 7890A) [32].

Crop yield was evaluated by determining, at the harvest of each year of the trial, the amount of grapes produced per hectare. Must quality was assessed by measuring total soluble solids (TSS) with a refractometer and titratable acidity by titration.

2.3.3. Arable Crop Rotation in Belgium

A field experiment was conducted in Merelbeke (Belgium), which focuses on an arable crop rotation that includes spring barley (*Hordeum vulgare* L.), leek (*Allium porrum* L.) and Italian ryegrass (*Lolium multiflorum* L.). A cover crop of white mustard (*Sinapis alba* L.) was sown in fall following spring barley and before leek cultivation. The soil at the experimental site is a Haplic Luvisol, 59.9% sand, 34.7% silt and 5.4% clay, pH of 5.94, 0.85% TOC. Agro climatic conditions were characterized by fully humid temperate climate, 879 mm annual rainfall and 10.7 °C mean annual temperature.

The treatments were: biochar (10.9 t C ha^{-1}), biowaste and green waste compost (10.9 t C ha^{-1}), biochar-blended compost, 10:90 w:w (10.9 t C ha^{-1}) and a control were only mineral N and K fertilizers were applied (Figure 3). The experimental design of the trial was completely randomized with four replicates. The biochar was applied in year 1, while the compost and the biochar-blended compost were applied in year 2. All plots received an equal dose of mineral N and K fertilizer according to crop requirements (no mineral P fertilizer was applied). The organic amendments were incorporated to a depth of 20–25 cm at time of application. The size of each plot was 90 m^2.



Site description: BIOCHAR field trial, ILVO, Merelbeke (Belgium)

- **Crop rotation:** spring barley – spring barley -white mustard (cover crop) – leek – Italian ryegrass
- **Agroclimatic conditions:**
  - ✓ Fully humid temperate climate
  - ✓ Annual rainfall: 879 mm/year
  - ✓ Mean annual T: 10.7°C
- **Coordinates:** 50°58′ N 3°46′ E
- **Soil:** Haplic Luvisol, 59.9% sand, 34.7% silt and 5.4% clay, pH of 6.38, 0.85% TOC
- **Soil amendments:** biochar, compost and biochar-blended compost (90/10). Dose: 10.9 ton C (on a dry matter basis) per hectare

Experimental design and chronogram

Key findings

- The single application of biochar, compost and biochar-blended compost clearly increased soil TOC and pH.
- Composts application significantly increased NO_3^- (in the first half year after application) and available K content. However, as a cover crop was grown, NO_3^- in the compost treated plots never exceeded the legal limit of 90 kg N ha^{-1}, indicating a low risk of N leaching.
- Total soil microbial biomass remained unchanged after the addition of all three amendments.
- Biochar showed no negative effect on crop yield, while composts increased yield and N content in white mustard.

Figure 3. Description of the field scale experiment in Belgium: arable crop rotation with vegetables.

Soil was sampled in October 2012, September 2013, and March 2015 at a depth of 0–25 cm. The agronomical evaluation involved soil characterization (physical, chemical and biological properties), crop yield, and plant nutritional status. Soil water content was measured gravimetrically on the 0–30 cm soil layer by oven drying at 105 °C for 24 h. Soil total organic carbon (TOC) and total N were measured by dry combustion at 1050 °C using a Skalar Primacs SLC TOC analyser (ISO 10694) and at 950 °C using a Thermo Flash 4000 N-analyser (ISO 13878), respectively. The pH was measured potentiometrically in a 1:5 soil:KCl (1M) extract according to ISO 10390. Hot water extractable C (HWC) was determined with a modification of the method of Ghani et al. [33]. Available K was determined by ICP in a 1:20 soil:ammonium lactate extract.

Biological properties were evaluated by determining total soil microbial biomass utilizing PLFA analysis [34].

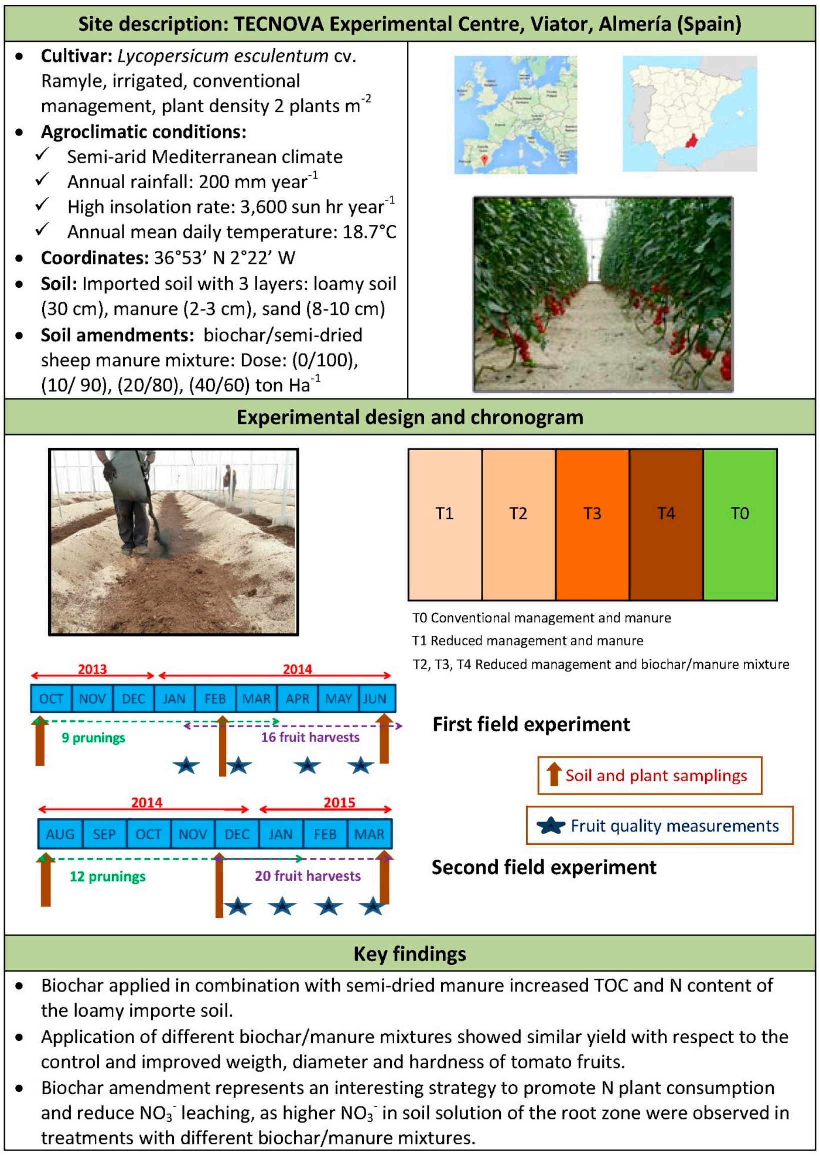
Crop yields were determined annually. N concentration of white mustard, leek, and Italian ryegrass were determined according to ISO 16634-1 and are reported on a dry weight base.

2.3.4. Greenhouse Grown Tomato Crop in Almeria (Spain)

The experiment was carried out in the Experimental Centre of the Technological Centre of TECNOVA, located in Southeast Spain (36°53′ N; 2°22′ W, 184 m elevation). The area belongs to a semi-arid Mediterranean climate, with an annual rainfall of 200 mm/year, which mainly falls during the months of September and October. The annual mean daily temperature is 18.7 °C.

The experiment was developed in one traditional greenhouse, with no heating and a passive ventilation system. The soil had three different layers: a loamy imported soil of 30 cm depth placed over the original soil, covered with a layer of semi-dried sheep manure (equivalent to an application dose of 100 t ha^{-1}) which is mechanically mixed with the loamy soil layer, and a layer of sand of 8 cm depth placed on its upper zone as a mulching. The treatments were as follows: T0 (100% sheep manure—conventional nutritional strategy), T1 (100% sheep manure), T2 (90% manure + 10% biochar), T3 (80% manure + 20% biochar), and T4 (60% manure + 40% biochar). The same treatments were performed the following years, but treatments T1, T2, T3 and T4 received a reduced strategy of irrigation and mineral fertilization based on the application of 30% less volume of water and amount of mineral fertilizers in comparison with the conventional strategy. Five different trial plots were planted with tomato crop to develop this experiment with a total area of 200 m^2 per trial plot (Figure 4).

The evolution of the concentration of TOC in the soil, NH_4^+, NO_3^- in the soil solution, and total N in the crop was monitored during the experiment. Three different soil samplings were performed (at a depth of 20 cm) per tomato crop at three different moments of the cropping season (at 0, 102 and 220 days after transplanting). TOC was measured using the Walkley-Black method. Total N, NH_4^+-N and NO_3^--N were determined using a Kjeldahl digester and a Büchi distillation unit. Aerial biomass production (stems, leaves and fruits) was measured at three different moments of the cropping season (0, 102 and 220 days after transplanting). Crop yield was characterized in each multiple harvesting episode. Total N concentration was measured three times in each tomato crop (at the beginning, at the middle, and at the end of the cropping season; which is 0, 102 and 220 days after transplanting) using a Kjeldahl digester and a Büchi distillation unit. Additionally, the following fruit quality parameters were evaluated: weight, diameter, hardness and sugar content. The measurement of hardness was made using a portable durometer (model 53215TP, Turoni, Forli, Italy); the content of sugar was characterized using a portable refractometer (model PAL-1, Atago, Tokyo, Japan). The measurements of hardness and sugar content were performed at three different positions in the fruit, and an average value was estimated per fruit and per treatment.



Site description: TECNOVA Experimental Centre, Viator, Almería (Spain)

- **Cultivar:** *Lycopersicum esculentum* cv. Ramyle, irrigated, conventional management, plant density 2 plants m^{-2}
- **Agroclimatic conditions:**
  - ✓ Semi-arid Mediterranean climate
  - ✓ Annual rainfall: 200 mm year^{-1}
  - ✓ High insolation rate: 3,600 sun hr year^{-1}
  - ✓ Annual mean daily temperature: 18.7°C
- **Coordinates:** 36°53′ N 2°22′ W
- **Soil:** Imported soil with 3 layers: loamy soil (30 cm), manure (2-3 cm), sand (8-10 cm)
- **Soil amendments:** biochar/semi-dried sheep manure mixture: Dose: (0/100), (10/ 90), (20/80), (40/60) ton Ha^{-1}

Experimental design and chronogram

T0 Conventional management and manure
T1 Reduced management and manure
T2, T3, T4 Reduced management and biochar/manure mixture

First field experiment

Second field experiment

Key findings

- Biochar applied in combination with semi-dried manure increased TOC and N content of the loamy importe soil.
- Application of different biochar/manure mixtures showed similar yield with respect to the control and improved weigth, diameter and hardness of tomato fruits.
- Biochar amendment represents an interesting strategy to promote N plant consumption and reduce NO_3^- leaching, as higher NO_3^- in soil solution of the root zone were observed in treatments with different biochar/manure mixtures.

Figure 4. Description of the field scale experiment at Almería (Spain): greenhouse tomato crop.

2.4. Statistics

Soil chemical, physical and biological data, and crops yields and quality data were analyzed with SPSS Statistics 19, using a one-way ANOVA with soil amendment as factor. Significant differences between means were determined by the SNK test. Correlations between variables were calculated using Pearson's correlation coefficient.

3. Results and Discussion

The main aim of soil application of organic matter is the enhancement of the soil's physical, chemical and biochemical properties in order to increase fertility (in terms of soil water content, C and N cycling, availability of elements, microbial biomass amount, respiration and denitrifying activity) and plant performances. For this reason, the results of the experimental trials are reported to specifically show the impact of the different amendments on soil fertility, crop yield, and quality.

3.1. Olive Orchard in Murcia (Spain)

3.1.1. Soil Fertility

The results at the end of the third year of the trial showed that biochar and biochar/compost mixture treatments led to the highest and most persistent increase in TOC (increase from the control of 50% for blend and 122% for biochar), whereas EN and EOC were always higher in compost amended plots (Table 3). More specifically, the increase with respect to the control for EN were 87% for compost and 68% for blend, while for EOC it was 73% for compost and 46% for blend. The application of a compost/biochar mixture showed a synergistic impact on the microbial processes transforming N in soil. The greatest effect was observed in the soil denitrification activity, which was up to four times higher in soil amended with the mixture of compost and biochar, compared to the rest of the treatments (Table 3). This increase may be due to an overall higher microbial activity in mixture-amended soils. Nitrifying bacterial populations showed a high spatial variability between plots and consequently the effect of the organic amendments was not clear. But in any case, the nitrifying bacterial population was considerably larger in the mixture treatment than in other treatments, evidencing some type of synergistic effect when compost and biochar were applied together. This effect was observed immediately after the first addition of the organic amendments, as previously reported for this field experiment [28].

Table 3. Soil fertility parameters after three years of field scale experiments for different cropping systems.

Parameter (unit)	Cropping System	Treatment [1]							
		Control		Compost		B + C [2]		Biochar	
pH	Crop rotation	5.94	a	6.4	bc	6.47	c	6.09	ab
Total organic C (%)	Olive orchard	1.33	a	1.50	a	2.00	b	2.95	c
	Vineyard S1	1.13	a	1.24	b	1.33	c	1.38	c
	Vineyard S2	1.73	a	1.78	b	1.83	b	1.81	b
	Vineyard S3	1.41	a	1.66	a	1.54	a	1.60	a
	Crop rotation	0.90	a	1.01	ab	1.05	b	1.06	b
	Tomato	1.25	a	na [3]		2.22	b	na	
Total N (%)	Olive orchard	0.15	a	0.15	a	0.19	a	0.17	a
	Vineyard	nd [4]		nd		nd		nd	
	Crop rotation	0.07	a	0.09	bc	0.09	c	0.08	abc
	Tomato	0.11	a			0.22	b		
Extractable organic C (mg kg^{-1})	Olive orchard	205	a	355	b	300	b	194	a
	Vineyard S1	48.8	a	53.5	a	62.0	a	60.4	a
	Vineyard S2	48.4	a	54.3	b	52.8	b	49.3	a
	Vineyard S3	38.8	a	47.2	b	46.9	b	38.3	a
	Crop rotation [5]	819	a	958	b	959	b	872	ab
Extractable N (mg kg^{-1})	Olive orchard	35.1	a	65.7	d	58.5	c	41.3	b
	Vineyard S1	3.6	a	5.1	b	6.5	c	4.7	ab
	Vineyard S2	9.7	b	9.9	b	10.1	b	8.7	a
	Vineyard S3	6.5	a	9.4	c	8.0	b	6.3	a
	Crop rotation	nd		nd		nd		nd	
$NO_3{}^-$–N [6] (mg kg^{-1})	Olive orchard	6.29	ab	4.56	a	7.7	b	7.83	b
	Vineyard S1	2.03	a	3.07	a	3.08	a	2.46	a
	Vineyard S2	14.9	b	17.8	c	19.7	c	11.8	a
	Vineyard S3	6.03	a	10.0	a	10.2	a	5.46	a
	Crop rotation	2.87	ab	3.38	bc	4.68	c	2.33	a

Table 3. *Cont.*

Parameter (unit)	Cropping System	Treatment [1]							
		Control		Compost		B + C [2]		Biochar	
NO_3^--N in soil solution ($g\ L^{-1}$)	Tomato	1.25	a	na		2.14	b	na	
Available K ($mg\ kg^{-1}$)	Olive orchard	nd		nd		nd		nd	
	Vineyard S1	23.7	a	24.9	a	24.0	a	20.4	a
	Vineyard S2	19.6	a	26.6	ab	29.3	b	22.1	ab
	Vineyard S3	33.4	a	46.8	b	36.9	ab	38.4	ab
	Crop rotation	137	a	183	b	184	b	146	a
Water content (%)	Olive orchard	1.48	a	1.23	a	1.41	a	1.43	a
	Vineyard S1	11.2	a	12.3	a	12.4	a	11.8	a
	Vineyard S2	18.9	a	18.9	a	19.2	ab	19.5	b
	Vineyard S3	13.4	a	14.4	a	14.2	a	14.1	a
	Crop rotation	13.9	a	14.2	a	14.4	a	14.0	a
DEA [7] ($mg\ N\ kg^{-1}\ h^{-1}$)	Olive orchard	7.6	a	14.4	b	33.2	c	6.7	a
Microbial respiration	Vineyard S1	295	a	364	b	382	b	290	a
($\mu g\ CO_2$-C g^{-1} soil)	Vineyard S2	272	a	323	b	360	c	287	a
Microbial biomass (nmol C g^{-1} soil)	Crop rotation	41.7	a	45.2	a	47.4	a	39.8	a

[1] For tomato cropping system control treatment refers to 100% sheep manure and B + C to a 40:60 biochar:sheep manure mixture on a dry weight basis; [2] B + C: biochar-blended compost; [3] na: not applicable; [4] nd: not determined; [5] hot water extractable C; [6] measured three month after amendments application; [7] DEA: denitrifying enzyme activity. For each row, different letters indicate significant differences among treatments according to SNK test ($p < 0.05$).

3.1.2. Crop Yield and Nutritional Status

The production of olives was not significantly affected by the type of amendment, even if the three amendments showed a trend towards an increase in production (Table 4). Regarding the olive trees nutritional status, the concentration of N was within the normal range and did not show any statistical difference among treatments, even though the compost and biochar treatments led to the highest N concentration in plants at the end of the experiment (Table 4). Concerning the remaining macro and micronutrients, there were no significant differences among the treatments. It seems that three years was not a sufficient period to allow changes in the orchard's nutritional status to be detected, which is probably a consequence of the slow response by olive trees to changes in fertilization practice [35].

Table 4. Parameters of crop production, nutritional status, and quality at the end of the trial period for different cropping systems.

Parameter (Unit)	Cropping System	Crop	Treatment [1]							
			Control		Compost		B + C [2]		Biochar	
Crop production										
Yield ($Mg\ ha^{-1}$)	Olive orchard		24.4	a	27.1	a	26	a	30.5	a
	Vineyard S1		7.3	a	8.9	a	12.0	b	8.1	a
	Vineyard S2		17.3	a	26.4	a	20.8	a	20.2	a
	Vineyard S3		5.5	a	7.9	a	8.2	a	4.6	a
	Crop rotation	White mustard [3]	0.9	a	2.0	b	1.9	b	1.2	a
	Crop rotation	Leek [3]	8.2	a	8.1	a	8.4	a	8.0	a
	Crop rotation	Italian ryegrass [3]	15.4	a	16.6	a	16.2	a	16.0	a
	Tomato		10.6	a	na [4]		10.8	a	na	
Crop nutritional status										
Total N ($mg\ g^{-1}$)	Olive orchard [5]		15.0	a	15.4	a	15.4	a	15.5	a
	Tomato [4]		25.2	a	na		23.5	a	na	
	Crop rotation	White mustard	27	a	32	b	33	b	28	a
	Crop rotation	Leek	23	a	27	a	26	a	23	a
	Crop rotation	Italian ryegrass	4.3	a	4.2	a	4.5	a	4.5	a

Table 4. *Cont.*

Parameter (Unit)	**Cropping System**	**Crop**	**Treatment** [1]							
			Control		**Compost**		**B + C** [2]		**Biochar**	
Crop quality										
Must acidity (g L^{-1})	Vineyard S1		4.4	a	5.0	c	4.8	bc	4.7	b
	Vineyard S2		6.9	a	7.9	b	7.7	bc	6.9	a
	Vineyard S3		5.7	a	6.1	a	5.7	a	6.0	a
Total soluble solids in must (° brix)	Vineyard S1		21.5	a	21.3	a	21.3	a	21.6	a
	Vineyard S2		16.9	a	17.6	a	16.9	a	16.7	a
	Vineyard S3		24.5	b	23.3	a	23.5	a	24.7	b
Fruit weight (g)	Tomato		73	a	na		85	b	na	
Fruit diameter (cm)	Tomato		4.9	a	na		5.3	b	na	
Fruit hardness (%)	Tomato		72	a	na		78	b	na	
Fruit sugar content (° brix)	Tomato		6.1	a	na		6.4	a	na	

[1] Tomato cropping system control treatment refers to 100% sheep manure and B + C to a 40:60 biochar:sheep manure mixture on a dry weight basis; [2] B + C: biochar-blended compost; [3] dry matter yield; [4] na: not applicable; [5] total N in leaves. For each row, different letters indicate significant differences among treatments according to the SNK test ($p < 0.05$).

3.2. Vineyards in Italy

3.2.1. Soil Fertility

The blend and biochar significantly increased soil water content with respect to the control in site S2 (Table 3). The increment in water content can be attributed to the modification of the physical properties of the soil (increase in porosity and active surface sites, enhancement of soil structure) caused by the addition of organic matter, which favours the capacity of the soil to store water [36].

The results clearly show that a single addition of the three organic amendments caused an increase in TOC, although not significant in S3, which was sustained throughout the whole period of the trial (Table 3). The increase in TOC with respect to the control, considering all the three sites, was 13.6%, 11.1% and 10.4% for biochar, biochar-blended compost and compost, respectively.

The application of composts and biochar-blended compost also had a positive impact on nutrient cycling, as it enhanced the content of EOC, EN, NO_3^- and K in soil, while biochar application did not affect the availability of nutritive elements (Table 3). Therefore, soil amendment with composts enhanced the availability of elements suitable for the activity and growth of soil microorganisms and plants [37]. Specifically, significant increase in available C recorded in compost-treated soils indicates that soil amendment could stimulate soil microbial biomass growth and activity, as has been demonstrated that easily available C may induce activation of microorganisms and is limiting for microbial growth [38].

Extractable N represents the primary source of mineralisable N and it has been used as an estimate of the N supplying capacity of soils and as an indicator of changes in soil and fertilizer management. Both compost and biochar-blended compost caused a sustained increase in the level of EN (data not shown) and such evidence highlights their capacity to supply plants with a low, but regular supply of available N throughout the whole vegetative season. This is an important feature in these soils characterized by low N availability, as it lowers the possibility to have N plant deficiencies during important stages, avoids excessive plant development, and decreases the risk of N leaching and N_2O gas emissions.

The compost and biochar-blended compost also had a positive impact on the soil microbial pool as shown by the increase in microbial respiration (Table 3). Respiration is a direct measurement of biological activity, integrating abundance and activity of microbial life, and providing an indication of soil health and the soil's ability to sustain plant growth.

3.2.2. Crop Yield and Quality

Compost and biochar-blended compost affected crop productivity, causing an increase in grape yield, and must quality, resulting in an increase of acidity and a decline in TSS content (Table 4). On the contrary, biochar did not affect grape yield and must quality. The increase in production is an important goal for low vigour sites in the hillslope area (S1 and S3, Figure 2), characterized by low and uneven yield and low canopy level. Therefore, the yield increase recorded in compost and biochar-blended compost-amended soils may have relevant practical implications, as compost application may represent a feasible strategy to recover vine vigour and enhance productivity. At the same time, organic matter application may extend ripening time and increase soil fertility. The recorded changes in must properties in soils amended with compost and biochar-blended compost are all favorable for a regular progression of the fermentation process and for the development and stability of high-quality wine and may represent a valuable oenological target and a strategy of adaptation to climate change [39]. In fact, an appropriate level of acidity favors the regular development of the fermentation processes and increases the longevity of the wine. In addition, a lower content of sugars results in wines with low alcohol grade, a characteristic that increases the market acceptance of the wine, as fresh and fruity wines are preferred for everyday consumption. Regarding climate change, the increase in temperature recorded in the last years causes an anticipated grape maturation that adversely affects wine quality, as the ripening process did not have a regular development [40]. The higher acidity and decrease in soluble solids are characteristics that counteract the anticipation in maturation [41].

3.3. Crop Rotation in Belgium

3.3.1. Soil Fertility

A single application of compost, biochar-blended compost and biochar caused a high and significant increase of the TOC content with respect to the control, even 1.5 (compost and biochar-blended compost) or 2.5 (biochar) years after application (Table 3). TOC increase with respect to the control was 12% for compost, 17% for biochar-blended compost, and 18% for biochar. Moreover, soil sampling three years after application in the control and the biochar plots at three different depths (0–25, 25–30 and 30–40 cm) revealed transport of biochar to the subsoil (>25 cm depth) due to tillage practices. In terms of C storage, this would increase the persistence of biochar in soil due to the combined effect of the natural recalcitrance of biochar and unfavorable conditions for decomposition at lower soil depth.

The organic amendments also resulted in a significant increase in soil pH, which was more obvious in the case of the two compost types (increase in pH of 0.46 units for compost, 0.53 for biochar-blended compost and 0.15 for biochar) (Table 3).

Regarding nutrients, both composts showed a remarkable fertilizer value, as they significantly increased the content of NO_3^- and extractable K. In particular, NO_3^- remained significantly higher (on average about 20 kg NO_3^--N ha^{-1} to a depth of 90 cm) in the compost treatments compared to the control in the first half year after application. This is in agreement with the known use of compost as a slow-release source of N [42]. For example, for vegetable, fruit and garden waste compost, the average percentage of N that becomes available for the crops during the post-application year is generally estimated at 10–15% [43], while the rest is released over time. However, the nitrate-N residue in the compost plots never exceeded the legal limit of 90 kg N ha^{-1}, indicating a low risk of N leaching, in case a catch crop is grown during winter.

The soil moisture content during the trial showed a clear, although mostly not significant, trend with the highest values for both compost treatments—intermediary for biochar and lowest for the control (Table 3).

Biological soil quality, estimated by PLFA analysis, was not affected by a single application of biochar, compost and/or biochar-blended compost (Table 3).

3.3.2. Crop Yield and Quality

No significant yield increase or decrease was observed in the main crops (i.e., spring barley, leek and Italian ryegrass) after the single application of biochar and/or compost, even if the composts provided high doses of N, P and K. As all treatments received an equal dose of mineral N and K fertilizers, we assume that N and K were non-limiting for plant growth in this field trial. On the contrary, a significant increase of yield was recorded for the cover crop (white mustard) in the compost plots (Table 4). As white mustard was sown as a catch crop in fall, it was not fertilized with mineral fertilizers and therefore benefited from the compost as a sole source of nutrients [44]. Regarding the nutritional status of the crops, compost application increased the N content in white mustard and leek, although the increase was significant only in the case of the cover crop.

3.4. Greenhouse Tomato in Almeria (Spain)

3.4.1. Soil Fertility

At the end of the experiment, TOC and total N in the first 20 cm depth of the loamy imported soil was higher in treatments receiving a mixture of manure and biochar in comparison with the plot amended only with manure (Table 3). Moreover, TOC was positively correlated with the rate of applied biochar ($r = 0.997$, $p < 0.05$). Similarly, concentrations of total N in the soil at the end of the experiment were correlated with the rate of biochar ($r = 0.80$, $p < 0.05$).

Biochar amendment has been proposed as an interesting strategy to retain nitrates in irrigated soils, in order to promote plant consumption of accumulated mineral N, and reduce nitrate leaching [45–47]. This beneficial effect of biochar was clearly shown in the second year of the field experiments, as biochar-amended plots that received a reduced amount of irrigation and mineral fertilization showed a higher concentration of nitrates in the soil solution of the root zone in comparison to the plot receiving only manure under the same irrigation and fertilization scheme (Table 3).

3.4.2. Crop Yield and Quality

The production of total aerial biomass (stems, leaves and fruits) and the total yield of the tomato crops were in the range normally found in the area for tomato cultivation in greenhouse and did not show any statistical difference among treatments that received different rates of biochar, even in the second year where treatments were managed with reduced irrigation and mineral fertilization (Table 4). Generally, total N content in leaves of all biochar treated plots was not statistically different from the control during the growing season, as tomato crops did not show symptoms of N deficiencies, in agreement with the results of a meta-analysis on the effect of biochar on tissue N content [48]. The substitution of a proportion of manure with biochar applied periodically as a soil amendment has proven to be an option to maintain soil fertility and to reduce leaching of nitrates in intensive horticulture areas.

The evaluated fruit quality parameters in all treatments receiving biochar were consistent with the quality standards required by the market. Moreover, the combination of a reduced strategy of irrigation and fertilization and a soil amendment based on a mixture of biochar and manure with a 40/60 proportion (treatment T4) showed fruits at the end of the cropping season with a significant 16%, 9% and 8% higher weight, diameter and hardness, respectively (Table 4).

4. Conclusions

The 3-year FERTIPLUS field experiments provided data for an agronomical evaluation of biochar, compost, and biochar-blended compost for different European agro-climatic regions based on different aspects of soil fertility, crop productivity, and quality. The results confirmed the potential of biochar to improve soil physical properties in three out of four trials and to achieve a long-lasting increase of soil C in all tested agro-climatic regions. No negative effects of pure biochar application were observed on soil quality or crop yield. This confirmed that the biochar used (prepared from lignocellulosic material) was not a direct source of nutrients. The role of biochar in nutrient cycling was indirect and attributed to enhancing soil properties (TOC, pH, water content), thus promoting the cycling and availability of the elements and nutrients.

However, this property requires a certain time after biochar application to be fully expressed (biochar aging) and therefore it is likely that the short time of the field trials did not allow the biochar to express its maximum potential. On the other hand, compost and biochar-amended composts were demonstrated to be effective as a source of nutrients and a potential driver to sustain and enhance soil biological activity.

Regarding crop performance, biochar did not show any detrimental effect, while compost and biochar-blended compost showed, in the case of vineyards and greenhouse tomato, a positive impact on crop yield and an enhancement of fruit quality parameters that are relevant for the development of good quality wine and market suitability of tomato. The results suggested that the utilized amendments are suitable for different agroclimatic conditions. They are all indicated for acidic soil, as they are alkaline materials and show a capacity to increase soil pH. Biochar is also particularly suited for all soils characterized by a TOC content beyond the threshold value (2%) required for proper soil functioning, such as in the case of olive and vineyard orchards in Italy and Spain. Due to the high stability of biochar towards decomposition in soil, its application makes sense for a long-lasting increase in SOM to benefit of all the key functions exerted by SOM in soil. Biochar is also indicated as a partial substitute for manure in artificial soils in intense greenhouse systems, due to its positive action on nitrate retention, which reduces the risks of leaching in intensive horticulture areas.

The application of compost and biochar-blended compost can serve as a partial substitute for mineral fertilizers due to the direct supply of nutritive elements and the enhancement of nutrients' cycling and availability and stimulation of the microbial pool.

Considering all the observed effects and the acknowledged positive impact of biochar on the composting process, soil application of biochar-blended composts represents a promising technical option to increase the sustainability of agricultural systems.

This site-specific agronomical evaluation provides useful information for farmers to integrate biochar into conventional agricultural practices, and for land managers and policy makers to develop measures promoting innovative technologies to recycle organic wastes into valuable products for use in agriculture.

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