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Impacts of Conventional and Agri-Food Waste-Derived Fertilizers on Durum Wheat Yield, Grain Quality, and Soil Health: A Two-Year Field Study in Greece and Southern Italy

Adele Muscolo [1,*], Kostantinos Zoukidis [2], Evangelous Vergos [2], Federica Alessia Marra [1], Ludovica Santoro [1], Mariateresa Oliva [1], Santo Battaglia [1], Angela Maffia [1] and Carmelo Mallamaci [1]

[1] Affiliation Agriculture Department, Mediterranea University, 89124 Reggio Calabria, Italy; federica.marra@unirc.it (F.A.M.); ludovica.santoro@unirc.it (L.S.); mariateresa.oliva@unirc.it (M.O.); santo.battaglia@unirc.it (S.B.); angela.maffia@unirc.it (A.M.); carmelo.mallamaci@unirc.it (C.M.)
[2] American Farm School of Thessaloniki, 570 01 Thermi, Greece; kzouki@afs.edu.gr (K.Z.); vvergos@afs.edu.gr (E.V.)
* Correspondence: amuscolo@unirc.it; Tel.: +39-09651694364

Abstract

Sustainable fertilization strategies are critical under climate change and the European Green Deal, particularly for Mediterranean cereal systems. Organic fertilizers derived from agro-industrial residues offer promising alternatives to conventional mineral inputs. This study evaluated RecOrgFert, a novel fertilizer composed of sulfur–bentonite and citrus-processing residues, in comparison with NPK (15-15-15) and horse manure across two years in Central Macedonia (Greece) and Apulia (Italy). Using a randomized complete block design, soil chemical and biological properties, plant growth, yield, and grain quality were assessed. RecOrgFert outperformed conventional fertilizers by enhancing soil fertility—raising organic matter 25–27% above control and further increasing it from 2023 to 2024 (up to +75% in Italy, +38% in Greece)—while improving cation exchange capacity, enzymatic activity, and soil water content. Wheat grown with RecOrgFert showed higher protein (up to 15.2%), antioxidant activity (DPPH > 37%, $ABTS^{+}$ > 26%), and phenolic and flavonoid content, with yields comparable to NPK. The unique sulfur and orange-residue composition distinguish RecOrgFert from standard fertilizers, promoting nutrient cycling, microbial activity, and bioactive compound accumulation. It represents a novel, circular, and climate-smart solution aligned with EU sustainability and circular economy objectives.

Keywords: organic fertilizer; soil fertility; wheat quality; agri-food waste recycling; sustainable agriculture

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1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops globally and serves as a staple food for a large portion of the world's population, providing approximately 20% of the daily caloric and protein intake [1]. To sustain the productivity required for global food security, conventional agricultural systems have long relied on synthetic nitrogen (N), phosphorus (P), and potassium (K) fertilizers. While these inputs are effective in increasing yields, their prolonged and excessive use is associated with significant environmental challenges, including soil acidification, nutrient leaching, loss of biodiversity, and elevated greenhouse gas emissions [2–4]

In the context of climate change and resource scarcity, the transition to sustainable fertilization practices has become a key priority in global and European agricultural policy. Organic fertilizers derived from agri-food industrial wastes are gaining attention as viable alternatives that can recycle nutrients, reduce wastes, and improve soil health [5–7]. These materials contribute to increase organic matter and nutrients which in turn enhance soil physical structure, microbial activity, and nutrient cycling processes, ultimately benefiting crop performance and sustainability [7,8]. Beyond agriculture, the industrial sector also generates waste materials that can be repurposed into value-added products, contributing to waste valorization efforts. One example is sulfur, a byproduct recovered from crude oil refining. This recovered sulfur holds potential for agricultural applications, especially in light of research indicating that sulfur deficiency can impair nitrogen uptake efficiency and result in crop proteins with reduced levels of sulfur-containing amino acids, such as methionine—an essential component influencing the nutritional quality of crops. The use of waste-derived fertilizers perfectly aligns with the principles of the circular economy, which promotes resource efficiency, waste minimization, and carbon footprint reduction across all sectors, including agriculture [9]. In this regard, the European Green Deal and the Circular Economy Action Plan strongly encourage the agricultural reuse of organic wastes, which can also help address the issue of declining soil organic matter in Mediterranean agroecosystems [10,11].

Despite their potential, the agronomic performance of waste-derived fertilizers can vary significantly depending on factors such as feedstock composition, treatment process, soil type, and climatic conditions. As a result, field-based studies are essential to validate their efficacy under different agro-environmental contexts [8]. Furthermore, while several studies assessed either yield or soil health separately, fewer have integrated both agronomic, soil quality, yield and wheat quality across multiple years and more geographical locations [4,5].

The Mediterranean region, characterized by its climate variability, limited water resources, and declining soil fertility, provides a relevant setting for evaluating the sustainability of fertilization practices. Greece and Southern Italy (Apulia), in particular, are important wheat-producing regions where alternative fertilization strategies could contribute to climate-resilient and environmentally sound cereal production systems [12]. The present study aimed to evaluate the impact of conventional mineral nitrogen, phosphorous and potassium (NPK, 15-15-15) or organic horse manure (HM) fertilizers and RecOrgFert, fertilizer derived from industrial and agri-food wastes specifically orange waste residue of agro-food industry and sulfur as residue of oil industry on wheat yield, grain quality, and soil health. Conducted over two consecutive years in contrasting Mediterranean environments—Apulia (Southern Italy) and Central Macedonia (Northern Greece)—this study seeks to: (1) compare the agronomic effectiveness of different fertilizer treatments; (2) assess their effects on soil chemical and biological properties; and (3) analyze yield and quality of wheat comparing the consistence of treatment responses across sites. By integrating multiple indicators of performance, this research provides practical insights to guide sustainable nutrient management and policy development in Mediterranean cropping systems [6,11].

2. Materials and Methods

2.1. Study Sites and Experimental Design

Field experiments were conducted over two consecutive cropping seasons (2023–2024) in two Mediterranean locations: Southern Italy (Apulia) in 17 hectares in Cambisol (Eutric, Haplic) with a sandy-loam texture (Sand, 37.2%; Silt, 49.9% and Clay 12.9%) and Central Macedonia Northern Greece (Thessaloniki) 12 hectares in Cambisol (Eutric, Calcaric, Clayic)

with clay-loam texture (Sand 38%; Silt 30% and Clay 32%), classified in accordance with FAO Word Reference Base (WRB). Both sites are representative of typical durum wheat (*Triticum durum* Desf.) cultivation areas in Mediterranean Environment but differ in soil types, climatic conditions, and agricultural history (Supplementary Material Figure S1. (a) Layout of the 17-hectare experimental field in Apulia, showing the distribution of the different treatments; (b) layout of the 12-hectare experimental field in Greece, showing the distribution of the different treatments, Tables S1–S3). Greece Thessaloniki (2023–2024) experienced a mild but stormy winter, a moderate spring, an exceptionally hot and dry summer, and a wet autumn with occasional severe storms (Supplementary Material Table S1). Southern Italy (Apulia) (2023–2024) experienced mild rainy winters, moderate springs, extremely hot and dry summers, and wetter autumns, typical of the Mediterranean inland climate (Supplementary Material Table S2). Basic management practices were the same in both locations (Greece and Italy): crop rotation with oat before wheat sowing; soil management including plowing, harrowing, and sowing with a precision seeder; and no phytosanitary treatments were applied.

In each location, a randomized complete block design (RCBD) was implemented with three replicates per treatment. The experimental treatments included: control (CTR)—No fertilized soil that represents the basic physical and chemical soil parameters; chemical fertilizer NPK (15-15-15); organic fertilizer (horse manure, HM); and sulfur bentonite plus orange wastes (RecOrgFert). RecOrgFert was produced by Steel Belt System s.r.l, in pellets of 3/4 mm diam. The mixture was formed by 85% of liquid sulfur, 10% of bentonite clay (as support and carrier), and 5% of fresh orange waste pastilled in a special belt system apparatus. Synthetic fertilizer NPK (15-15-15) containing 150 g/kg of N, 150 g/kg P_2O_5 and 150 g/kg of K_2O; HM containing 20 g/kg of N, 20 g/kg of P_2O_5, and 15 g/kg of K_2O. RecOrgFert composed by sulfur (85%)–bentonite (10%) + orange residue (5%), containing 15 g/Kg of N, 49 g/Kg of K and 1.09 g/Kg of P_2O_5.

Fertilizers were applied pre-sowing in the second half of December and at the vegetative state (25 cm height) at the end of February, at rates standardized to equivalent nitrogen content (150 kg N ha^{-1}), following local agronomic guidelines. At the Apulia site, the total experimental area of 17 hectares was divided into four main plots of approximately 4 hectares each, assigned as follows: control, NPK, RecOrgFert and horse manure. Each plot measured roughly 1335 m in length and 90 m in width, ensuring uniformity, particularly with respect to altitude, which ranged from 147 m to 203 m. Each main plot was further subdivided into three 1.33-hectare subplots, which served as replicates for the experimental treatments. At the Thessaloniki site, the 12-hectare area was similarly divided into four main plots of 3.0 hectares each, maintaining homogeneity among plots (Figure S1a,b). Each main plot was further subdivided into three 1-hectare subplots, which served as replicates for the experimental treatments.

2.2. Soil Analysis

Soil samples were collected from the upper 0–35 cm layer of each plot at three sampling times: (i) before the start of the experiment (T0, baseline), (ii) immediately after harvest in 2023, and (iii) immediately after harvest in 2024. For each plot, five subsamples were taken and combined into a composite sample for analysis. The choice of a 0–35 cm sampling depth reflects the active root zone of durum wheat, where nutrient uptake occurs predominantly, thus making this layer representative for assessing comparative soil conditions relevant to wheat growth and nutrient availability. Therefore, this sampling depth was considered representative for assessing comparative soil conditions relevant to wheat growth and nutrient availability. For each plot, five subsamples were taken, combined into a composite sample, and analyzed for various soil properties

The initial soil characteristics determined at time zero are reported in Table S3 of the Supplementary Materials. Results of soil analyses after harvest are presented in Tables 1 and 2 of the main text.

Table 1. Chemical and biochemical properties of the soil in the experiment in Greece.

	CTR	NPK	HM	RecOrgFert
		2023		
pH	8.0 ^{a}A ± 0.1	7.9 ^{b}A ± 0.1	7.9 ^{b}A ± 0.1	7.9 ^{b}A ± 0.1
OC	2.32 ^{c}A ± 0.15	4.00 ^{a}A ± 0.20	3.44 ^{b}A ± 0.18	2.34 ^{c}B ± 0.15
OM	4.0 ^{c}A ± 0.25	6.90 ^{a}A ± 0.30	5.93 ^{b}A ± 0.28	4.03 ^{c}B ± 0.25
C/N	19.33 ^{b}A ± 1.2	25.00 ^{a}B ± 1.5	22.93 ^{a}A ± 1.4	18.00 ^{b}B ± 1.0
CEC	12.73 ^{b}B ± 1.0	10.72 ^{b}B ± 1.1	13.60 ^{a}B ± 1.2	10.71 ^{b}B ± 1.0
Tot N	0.12 ^{b}B ± 0.01	0.16 ^{a}A± 0.01	0.15 ^{a}A ± 0.01	0.13 ^{b}A ± 0.01
EC	0.37 ^{b}B ± 0.03	0.40 ^{b}B ± 0.02	0.40 ^{b}B ± 0.02	0.43 ^{a}A ± 0.02
WC	13.10 ^{ab}A ± 1.5	11.10 ^{b}A ± 1.3	12.00 ^{ab}A ± 1.4	16.40 ^{a}A ± 1.8
		2024		
pH	8.0 ^{a}A ± 0.1	7.9 ^{b}A ± 0.1	7.7 ^{c}A ± 0.1	7.6 ^{c}B ± 0.1
OC	2.5 ^{c}A ± 0.16	4.10 ^{a}A ± 0.20	3.0 ^{b}B ± 0.16	3.2 ^{b}A ± 0.18
OM	4.4 ^{c}A ± 0.28	7.1 ^{a}A ± 0.35	5.2 ^{b}B ± 0.28	5.5 ^{b}A ± 0.30
C/N	14.2 ^{c}B ± 1.2	29.3 ^{a}A ± 1.6	23.4 ^{b}A ± 1.3	29.0 ^{a}A ± 1.5
CEC	22.8 ^{c}A ± 2.0	23.4 ^{bc}A ± 2.1	28.9 ^{a}A ± 2.3	24.1 ^{ab}A ± 2.2
Tot N	0.18 ^{a}A ± 0.02	0.14 ^{b}A ± 0.01	0.13 ^{b}A ± 0.01	0.11 ^{c}A ± 0.01
EC	0.82 ^{a}A ± 0.05	0.50 ^{b}A ± 0.03	0.57 ^{b}A ± 0.03	0.44 ^{b}A ± 0.02
WC	13.9 ^{b}A ± 1.5	12.0 ^{b}A ± 1.4	14.2 ^{ab}A ± 1.5	14.9 ^{a}A ± 1.6

CTR (control) = soil without fertilizer; NPK = nitrogen–phosphorus–potassium; HM = horse manure; RecOrgFert = bentonite sulfur + orange pomace. pH; OC = organic carbon (%); OM = organic matter (%); C/N = carbon–nitrogen ratio; CEC = cation exchange capacity (meq/100 g); Tot N = total nitrogen (%); EC = electrical conductivity (dS/m); WC = soil moisture (%). Data are the means of three replicates ± standard deviation. Different lowercase letters in the same row indicate significant differences (Tukey's test. $p \leq 0.05$). Different uppercase letters in the same column indicate significant differences (Tukey's test. $p \leq 0.05$) for the same parameters between the different years.

Table 2. Plant growth and grain biochemical parameters in the experiment in Greece (2023 and 2024).

	CTR	NPK	HM	RecOrgFert
		2023		
Plant height	176.0 ^{b}A ± 4.5	202.0 ^{a}A ± 5.0	203.0 ^{a}A ± 4.8	181.0 ^{ab}A ± 4.3
Seed/ear	35 ^{b}A ± 3	41 ^{a}B ± 3	37 ^{b}A ± 3	42 ^{a}B ± 2
Yield	0.177 ^{ab}A ± 0.018	0.198 ^{a}A ± 0.015	0.175 ^{ab}A ± 0.017	0.157 ^{b}A ± 0.016
Dry Seed	0.7 ^{b}A ± 0.1	1.0 ^{ab}A ± 0.1	2.2 ^{a}A ± 0.2	1.1 ^{ab}A ± 0.1
Proteins	12.0 ^{b}A ± 0.8	12.3 ^{ab}B ± 0.9	10.5 ^{c}B ± 0.8	15.1 ^{a}A ± 1.0
Dry gluten	14.1 ^{b}B ± 1.0	21.6 ^{a}A ± 1.2	18.9 ^{a}A ± 1.1	20.0 ^{a}B ± 1.1
β-carotene	0.50 ^{b} B ± 0.05	0.61 ^{ab}B ± 0.06	0.66 ^{a}B ± 0.07	0.62 ^{ab}B ± 0.06
TP	19.87 ^{c}A ± 0.85	21.76 ^{b}A ± 0.92	22.31 ^{ab}A ± 0.97	23.02 ^{a}A ± 1.04
TF	10.02 ^{c}B ± 0.47	18.89 ^{a} B ± 0.76	16.94 ^{b}A ± 0.73	17.62 ^{a}B ± 0.81
DPPH	32.85 ^{b}A ± 1.22	35.01 ^{ab}A ± 1.35	35.89 ^{a}A ± 1.33	36.45 ^{a}A ± 1.41
$ABTS^{+}$	23.67 ^{c}B ± 1.03	24.02 ^{c}A ± 1.18	24.88 ^{b}B ± 1.15	25.91 ^{a}A ± 1.26
		2024		
Plant height	161.0 ^{c}B ± 4.0	190.2 ^{a}B ± 4.5	186.8 ^{a}B ± 4.2	173.0 ^{b}A ± 4.1
Seed/ear	36 ^{b}A ± 3	53 ^{a}A ± 4	36 ^{b}A ± 3	50 ^{a}A ± 3
Yield	0.165 ^{ab}A ± 0.06	0.175 ^{a}B ± 0.07	0.139 ^{b}B ± 0.013	0.152 ^{a}A ± 0.05
Dry Seed	0.5 ^{ab}A ± 0.1	0.4 ^{b} B ± 0.1	1.1 ^{a}B ± 0.1	0.6 ^{ab}B ± 0.1
Proteins	12.8 ^{b}A ± 0.9	14.7 ^{ab}A ± 1.1	14.9 ^{a}A ± 1.0	16.6 ^{a}A ± 1.2
Dry gluten	18.0 ^{b}A ± 1.2	20.0 ^{a}A ± 1.1	17.8 ^{b}A ± 1.0	23.4 ^{a}A ± 1.3

Table 2. *Cont.*

	CTR	NPK	HM	RecOrgFert
β-carotene	2.20 ^{b}A ± 0.20	2.32 ^{ab}A ± 0.21	2.35 ^{a}A ± 0.22	2.29 ^{ab}A ± 0.20
TP	12.03 ^{b}B ± 0.56	11.37 ^{b}B ± 0.61	20.92 ^{a}B ± 1.02	19.65 ^{a}B ± 0.94
TF	11.12 ^{c}A ± 0.49	19.91 ^{a}A ± 0.92	17.41 ^{b}A ± 0.87	22.74 ^{a}A ± 1.03
DPPH	15.88 ^{c}B ± 0.88	23.45 ^{b}B ± 1.21	29.87 ^{a}B ± 1.38	26.12 ^{ab}B ± 1.30
$ABTS^{+}$	25.33 ^{b}A ± 1.11	26.12 ^{ab}A ± 1.25	28.15 ^{a}A ± 1.33	27.03 ^{a}A ± 1.19

CTR (control) = soil without fertilizer; NPK = nitrogen–phosphorus–potassium; HM = horse manure; RecOrgFert = bentonite sulfur + orange pomace. Plant height (cm); Seed/ear; Yield (Kg/m^2); Dry Seed (g/plant); Proteins (%); Dry gluten (% s.s.); β-carotene (mg/100 g). TP = total phenols (mg GAE g^{-1}); TF = total flavonoids (mg QE g^{-1}); DPPH = 2.2-difenil-1-picrilidrazile (% inhibition); $ABTS^{+}$ = 2.2′-azino-bis-3-etilbenzotiazolin-6-solfonato (% inhibition). Data are the means of three replicates ± standard deviation. Different lowercase letters in the same row indicate significant differences (Tukey's test. $p \leq 0.05$). Different uppercase letters in the same column indicate significant differences (Tukey's test. $p \leq 0.05$) for the same parameters between the different years.

Electrical conductivity (EC) was measured in a 1:5 (soil–distilled water) suspension, shaken mechanically at 15 rpm for 1 h to dissolve soluble salts, and recorded using a Hanna conductivity meter. Soil pH was determined in a 1:2.5 soil-to-water suspension using a glass electrode. Organic carbon content was quantified via the dichromate oxidation method, as described by Walkley and Black [13]. Total nitrogen (TN) was determined using the Kjeldahl digestion technique [14], and the carbon-to-nitrogen (C/N) ratio was calculated accordingly. Water-soluble phenolic compounds were extracted following the procedures outlined by Kaminsky and Müller [15,16]. All analyses were performed following standardized protocols as outlined in ISO 10390 and ISO 14240 [17,18]. Soil classification followed the FAO World Reference Base (WRB) system.

2.3. Yield Measurements

At crop maturity, wheat plants were manually harvested from a 4 m^2 area in each plot to avoid edge effects. The following yield parameters were recorded: plant height (cm), Seed/ear; Yield (Kg/m^2), calculated on the basis of the total mass of grain harvested and corrected to 13% moisture content, following standard normalization procedures [19]. Dry seed weight (g/plant) was determined to assess seed quality while avoiding the influence of moisture. Grain samples were dried in an oven at a controlled temperature until they reached constant weight, and the dry weight was then measured in grams (g) [19].

2.4. Grain Quality Analysis

Grain quality in terms of protein and gluten content, beta-carotene, total phenols and total flavonoids, antioxidant capacity ($ABTS^{+}$ and DPPH) was assessed using a subsample of dried and cleaned kernels from each plot. Protein content (%) was measured by using near-infrared spectroscopy (NIRS), a widely adopted non-destructive method for evaluating grain quality [20]. Gluten content and index have been measured by standard wet chemistry (ICC method No. 137/1), which provides robust indicators of baking quality [21]. The β-carotene content was determined by extraction with a solvent mixture (acetone–ethanol–hexane, 1:1:2, $v/v/v$), followed by spectrophotometric quantification at 450 nm, according to Saini et al. [22]. Results were expressed in mg/100 g of dry weight. Grain moisture content was adjusted to 13% for standardization. Total phenolic content was quantified using the Folin–Ciocalteu method [23], as previously described by Velioglu et al. [24]. For total flavonoid content, a colorimetric assay based on complex formation with aluminum chloride was employed, following the protocol developed by Djeridane et al. [25]. Antioxidant capacity was assessed using two standard assays. The $ABTS^{+}$ radical cation decolorization assay was performed according to the method of Re et al. [26], while the DPPH free radical scavenging assay, utilizing 2,2-diphenyl-1-picrylhydrazyl,

followed the procedure outlined by Barreca et al. [27]. Analytical precision was verified using certified reference materials. All tests were conducted in triplicate.

2.5. Statistical Analysis

Analysis of variance (ANOVA) was performed for all data sets. One-way ANOVA followed by Tukey's HSD (honestly significant difference) test was used to assess the effects of fertilizers on the various measured parameters. Comparisons were conducted to assess the effects of fertilizers on each individual parameter in respect to control. To explore the relationships between soil properties and crop parameters, correlation analyses were performed using the changes (Δ) in soil properties and crop quality traits induced by the different fertilizers. For each soil parameter, Δ values (e.g., ΔpH, ΔOC, ΔOM, ΔC/N, etc.) were calculated as the difference between post-harvest values and the baseline values measured before treatment application (time zero). These Δ values were then correlated with the corresponding changes in crop parameters (e.g., ΔProteins, ΔDry gluten, Δβ-carotene). Pearson correlation matrix analysis was applied to these datasets.

All statistical analyses were performed using MATLAB (version R2024b, The MathWorks Inc., Natick, MA, USA). Effects were considered significant at $p \leq 0.05$.

3. Results

3.1. Experiments in Central Macedonia Greece

3.1.1. Soil Properties

Over the two-year period, all fertilization treatments induced significant changes in soil chemical parameters compared to the control (CTR), with distinct trends across 2023 and 2024. In 2023 (Table 1), the application of NPK significantly increased organic matter (OM) (6.9%) compared to the control (4.0% OM), indicating a rapid nutrient soil incorporation that improved water retention, soil structure and nutrient availability. Horse manure (HM) and RecOrgFert also enhanced these parameters, although to a lesser extent. By 2024 (Table 1), OM were the highest under NPK (7.1%) and RecOrgFert (5.5%), with RecOrgFert showing notable improvement from the previous year (+37.5%). Interestingly, the increment of organic matter in percentage over the two years was more in presence of RecOrgFert (+25%) than NPK (+2.8%). CEC increased across all treatments, particularly under HM (28.92 meq/100 g). Soil pH decreased slightly across treatments in 2024 compared to 2023, under RecOrgFert (from 7.9 to 7.6), due to the presence of sulfur that acidify the soil overtime. Electrical conductivity increased in 2024 compared to 2023 except for RecOrgFert suggesting higher soluble salt content.

3.1.2. Plant Growth and Yield

NPK and RecOrgFert treatments consistently improved plant height and seed set across both years. In 2023 (Table 2), plants grown with NPK and HM were the tallest (~202–203 cm), whereas RecOrgFert produced the highest seeds per ear (42). In 2024, overall plant height declined—likely due to climatic variability—yet NPK (190.2 cm), HM (186.8 cm), and RecOrgFert (173.0 cm) still outperformed the control. Seed/ear values increased in 2024, particularly under NPK (53) and RecOrgFert (50). Yield was highest under NPK in both years (0.198 Kg/m^2 in 2023; 0.175 Kg/m^2 in 2024), followed by RecOrgFert. Although HM promoted higher dry seed mass in 2023 (2.2 g/plant), this benefit diminished in 2024, while RecOrgFert maintained stable yields.

3.1.3. Grain Biochemical Quality

Protein and gluten contents were enhanced under RecOrgFert, reaching 16.6% and 23.4% in 2024, respectively, indicating improved nutritional quality. Interestingly, β-

carotene content nearly tripled across all treatments, rising from ~0.62 to >2.29 mg/100 g between years, suggesting strong environmental or varietal influences.

RecOrgFert and HM proved most effective in enhancing phenolic compounds and antioxidant capacity, though their relative performance varied across years. In 2023 (Table 2), RecOrgFert clearly dominated, showing the highest total phenols (23.02 mg GAE/g), strong $ABTS^+$ activity (25.91%), and the greatest DPPH scavenging capacity (36.45%), suggesting a robust induction of antioxidant pathways. By contrast, in 2024, the phenolic profile shifted: HM produced the highest total phenols (20.92 mg GAE/g), while RecOrgFert excelled in flavonoid accumulation (22.74 mg QE/100 g), indicating that different fertilizer strategies may favor distinct classes of phenolics. Antioxidant assays further reflected this shift—HM led in DPPH activity (29.87%), pointing to stronger radical scavenging, whereas both RecOrgFert and HM sustained high $ABTS^+$ activities (>27%), demonstrating consistently enhanced antioxidant potential relative to the control. These results highlight that while RecOrgFert stimulates a broad antioxidant response, HM appears particularly effective under variable conditions in maintaining phenolic content and specific antioxidant activities.

3.1.4. Soil and Grain Parameters: The Correlation

Regarding the results of Greece in the first year (2023), representing in Figure S2 (Supplementary Material), in the control (CTR), correlations revealed a predominantly negative pattern: pH, organic carbon (ΔOC), organic matter (ΔOM), and water content (ΔWC) were negatively correlated with ΔProteins, ΔDry gluten, Δβ-carotene, and antioxidant capacity. Conversely, electrical conductivity (ΔEC) showed strong positive correlations with nutritional parameters (ΔProteins, ΔDry gluten, and Δβ-carotene). The ΔC/N ratio and total nitrogen (ΔTotN) displayed more variable relationships, with positive values mainly associated with antioxidants. In the NPK treatment, ΔOM, ΔC/N ratio, ΔTotN, and ΔEC were strongly and positively correlated with ΔProteins, ΔDry gluten, and Δβ-carotene. By contrast, ΔpH and ΔWC were negatively correlated with most variables. Antioxidant capacity was primarily correlated with ΔC/N ratio, ΔTotN, and ΔEC. In the HM treatment, ΔOM was positively correlated with ΔProteins, ΔDry gluten, and Δβ-carotene, but negatively with total polyphenols (ΔTP) and flavonoids (ΔTF). Both ΔOC and ΔEC showed strong negative correlations with ΔProteins, ΔDry gluten, and Δβ-carotene. A similar trend was observed for ΔpH, which was negatively related to nutritional parameters but positively associated with antioxidant activity (particularly $\Delta ABTS^+$). Finally, ΔTotN and the ΔC/N ratio showed positive correlations with ΔTP and antioxidants. In the RecOrgFert treatment, ΔOC and ΔOM were positively correlated with nutritional parameters (ΔProteins, ΔDry gluten, and Δβ-carotene). Conversely, ΔpH was negatively correlated with nutrients but positively related to ΔTP and ΔDPPH. The ΔC/N ratio and cation exchange capacity (ΔCEC) were positively correlated with $\Delta ABTS^+$, while ΔTotN and ΔEC exhibited weak or variable correlations. ΔWC showed only weak positive relationships with nutritional traits. (Figure S2, Supplementary Materials).

Regarding the results from Greece in the second year (2024), the correlation matrix (Figure S3, Supplementary Materials) for the control (CTR) revealed clear trends. Strong positive correlations were observed between ΔOC, ΔOM, ΔC/N, ΔCEC, and ΔWC with ΔProteins and Δβ-carotene, whereas ΔTotN showed negative correlations with these traits. Organic-related variables (ΔOC, ΔOM, ΔC/N, ΔCEC, and ΔWC) were negatively associated with ΔTP and ΔTF but displayed positive associations with the antioxidant activities ΔDPPH and $\Delta ABTS^+$. In contrast, ΔpH exhibited negative correlations with most nutritional traits, particularly with $\Delta ABTS^+$ (Figure S3, Supplementary Materials).

In the NPK treatment, negative correlations emerged between ΔpH, ΔOC, ΔOM, and ΔC/N with ΔProteins and ΔTF. Regarding antioxidants, ΔDPPH was strongly and positively correlated with ΔpH, ΔOC, ΔOM, and ΔC/N, whereas $\Delta ABTS^+$ was negatively correlated with almost all variables.

In the HM treatment, ΔpH showed strong negative correlations with ΔProteins, ΔDry gluten, Δβ-carotene, ΔTP, and ΔDPPH, while ΔOC and ΔOM exhibited weak or variable associations. In contrast, ΔC/N, ΔCEC, ΔTotN, ΔEC, and ΔWC displayed strong positive correlations with nutritional components, with ΔEC and ΔWC being particularly closely related to ΔProteins and Δβ-carotene. With respect to antioxidants, ΔDPPH correlated positively with ΔC/N and ΔTotN, while $\Delta ABTS^+$ showed weak positive associations with ΔpH and ΔOM.

In the RecOrgFert treatment, ΔpH correlated strongly and positively with ΔProteins, ΔDry gluten, and Δβ-carotene, but negatively with ΔTP and ΔDPPH. On the other hand, ΔOC and ΔOM were positively correlated with antioxidants (ΔTF, ΔDPPH, and $\Delta ABTS^+$), but negatively with nutrients and Δβ-carotene. ΔCEC showed positive correlations with both nutrients and $\Delta ABTS^+$, whereas ΔTotN and ΔEC were negatively associated with ΔProteins, ΔDry gluten, Δβ-carotene, and $\Delta ABTS^+$.

Regarding the results of Italy in the first year (2023), representing in Figure S4 (Supplementary Material), in the control (CTR), positive correlations were observed between ΔOC, ΔOM, ΔTotN, and ΔEC with ΔProteins and ΔDry gluten, while ΔWC was negatively associated with these nutritional traits. Total polyphenols (ΔTP) and flavonoids (ΔTF) were negatively correlated with ΔpH and ΔCEC, whereas the antioxidants ΔDPPH and $\Delta ABTS^+$ showed positive correlations with ΔOC, ΔOM, and ΔC/N. Interestingly, ΔpH was positively correlated with Δβ-carotene but negatively with ΔTP and ΔTF.

In the NPK treatment, ΔOC and ΔOM were positively correlated with ΔProteins but negatively with ΔC/N. Nutritional variables (ΔProteins, ΔDry gluten, and Δβ-carotene) were mainly associated with ΔCEC and ΔWC. ΔTF showed a negative correlation with ΔEC, whereas ΔDPPH was positively associated with ΔOC, ΔOM, ΔCEC, and ΔWC. $\Delta ABTS^+$ appeared primarily correlated with ΔTotN, while showing negative correlations with ΔEC. In the HM treatment, strong negative correlations were detected between ΔpH and ΔC/N with Δβ-carotene and other nutritional traits. ΔOM was positively correlated with ΔDry gluten, while ΔOC was positively associated with ΔProteins and Δβ-carotene. With regard to antioxidants, ΔTP displayed negative correlations with ΔOM, ΔC/N, and ΔCEC, whereas $\Delta ABTS^+$ was positively related to ΔOC, ΔOM, and ΔWC. In the RecOrgFert treatment, strong positive correlations were observed between ΔOM and ΔEC with ΔProteins and ΔDry gluten, whereas ΔOC was negatively correlated with Δβ-carotene. ΔCEC and ΔWC showed weak positive associations with nutritional traits. Antioxidants presented a more complex pattern: ΔOC and ΔOM were strongly negatively correlated with $\Delta ABTS^+$ but positively associated with ΔTF and ΔDPPH; in addition, ΔCEC and ΔTotN were positively correlated with ΔDPPH. (Figure S4, Supplementary Material). Overall, this treatment displayed a mixed correlation profile, with ΔOM and ΔEC supporting nutritional traits, while ΔOC and ΔpH appeared to play a greater role in shaping antioxidant responses.

Regarding the results of Italy in the second year (2024), representing in Figure S5 (Supplementary Material), In the control (CTR), positive correlations were observed between ΔProteins, ΔpH, the ΔC/N ratio, and ΔTotN, whereas ΔDry gluten was mainly associated with organic matter (ΔOM). Δβ-carotene showed positive correlations with electrical conductivity (ΔEC), ΔC/N ratio, and ΔCEC, while antioxidant activity (ΔDPPH and $\Delta ABTS^+$) displayed contrasting patterns. In the NPK treatment, proteins were positively correlated with ΔCEC and ΔOM, while ΔDry gluten showed negative correlations with ΔpH, ΔOC, and ΔTotN. Δβ-carotene was positively associated with ΔOM and ΔTotN but negatively

with ΔC/N and ΔEC. Phenolic compounds (ΔTP and ΔTF) exhibited positive correlations with ΔpH, ΔOC, ΔOM, ΔWC, and ΔTotN, whereas antioxidant activity showed variable trends, being positively associated with ΔEC but negatively with ΔOC and ΔTotN. In the HM treatment, ΔProteins were negatively correlated with ΔpH, ΔC/N ratio, and ΔCEC, but positively with ΔTotN, ΔOM, and ΔOC. ΔDry gluten was positively associated with ΔTotN, while Δβ-carotene showed positive correlations with ΔC/N ratio and negative correlations with ΔOC and ΔOM. Antioxidant activities exhibited weaker and less consistent associations. The RecOrgFert treatment generated strong and consistent correlations. ΔProteins were positively related to ΔC/N ratio, ΔOM, and ΔEC, but negatively with ΔWC. ΔDry gluten was positively associated with ΔOC and ΔWC, whereas Δβ-carotene showed strong positive correlations with ΔpH. Phenolic compounds (ΔTP and ΔTF) were mainly negatively associated with ΔOM and ΔC/N ratio, while antioxidant activity ($\Delta ABTS^{+}$) displayed a markedly positive correlation with ΔpH (Figure S5, Supplementary Material).

3.2. Experiments in Italy (Apulia)

3.2.1. Soil Properties

In Apulia, soil properties responded distinctly to both organic and synthetic amendments. In 2023 (Table 3), the control plot exhibited the highest organic carbon (OC) content (1.24%), while NPK, HM, and RecOrgFert all showed comparably lower values (~0.94–0.97%). This pattern suggests limited short-term mineralization and incorporation of organic matter following the initial application of amendments.

Table 3. Chemical and biochemical properties of soil in the experiment in Italy (Apulia, 2023–2024).

	CTR	NPK	HM	RecOrgFert
		2023		
pH	7.60 ^{b}A ± 0.12	7.80 ^{a}A ± 0.09	7.70 ^{ab}A ± 0.08	7.80 ^{a}A ± 0.11
OC	1.24 ^{a}A ± 0.18	0.95 ^{b}B ± 0.22	0.94 ^{b}A ± 0.19	0.97 ^{b}B ± 0.26
OM	2.14 ^{a}A ± 0.31	1.64 ^{b}B ± 0.28	1.62 ^{b}A ± 0.24	1.67 ^{b}B ± 0.35
C/N	0.12 ^{a}A ± 0.015	0.12 ^{a}A ± 0.018	0.13 ^{a}B ± 0.020	0.09 ^{b}A ± 0.012
CEC	29.50 ^{a}A ± 3.20	27.90 ^{b}A ± 2.90	26.20 ^{b}A ± 3.40	19.30 ^{c}B ± 2.60
Tot N	0.15 ^{a}A ± 0.025	0.11 ^{b}A ± 0.032	0.12 ^{b}A ± 0.035	0.09 ^{c}B ± 0.028
EC	0.36 ^{a}B ± 0.08	0.34 ^{a}B ± 0.12	0.34 ^{a}B ± 0.11	0.33 ^{a}B ± 0.09
WC	12.93 ^{b}A ± 2.10	11.21 ^{b}A ± 1.95	12.29 ^{b}A ± 2.25	15.98 ^{a}A ± 2.80
		2024		
pH	7.80 ^{a}A ± 0.14	7.80 ^{a}A ± 0.10	7.80 ^{a}A ± 0.11	7.80 ^{a}A ± 0.13
OC	1.34 ^{c}A ± 0.31	1.87 ^{a}A ± 0.42	0.95 ^{d}A ± 0.24	1.64 ^{a}A ± 0.38
OM	2.31 ^{b}A ± 0.12	3.22 ^{a}A ± 0.58	1.64 ^{d}A ± 0.12	2.93 ^{a}A ± 0.41
C/N	0.14 ^{b}A ± 0.022	0.10 ^{c}A ± 0.016	0.20 ^{a}A ± 0.028	0.12 ^{b}A ± 0.019
CEC	29.50 ^{a}A ± 2.10	27.10 ^{a}A ± 1.60	16.50 ^{c}B ± 1.40	26.1 ^{a}A ± 1.80
Tot N	0.19 ^{a}A ± 0.045	0.18 ^{a}A ± 0.038	0.19 ^{a}A ± 0.042	0.20 ^{a}A ± 0.048
EC	0.71 ^{b}A ± 0.15	0.69 ^{b}A ± 0.13	0.70 ^{b}A ± 0.14	0.91 ^{a}A ± 0.18
WC	14.01 ^{a}A ± 1.40	12.12 ^{a}A ± 1.15	13.89 ^{a}A ± 2.50	13.97 ^{a}A ± 2.65

CTR (control) = soil without fertilizer; NPK = nitrogen–phosphorus–potassium; HM = horse manure; RecOrgFert = bentonite sulfur + orange pomace. pH; OC = organic carbon (%); OM = organic matter (%); C/N = carbon–nitrogen ratio; CEC = cation exchange capacity (meq/100 g); Tot N = total nitrogen (%); EC = electrical conductivity (dS/m); WC = soil moisture (%). Data are the means of three replicates ± standard deviation. Different lowercase letters in the same row indicate significant differences (Tukey's test. $p \leq 0.05$). Different uppercase letters in the same column indicate significant differences (Tukey's test. $p \leq 0.05$) for the same parameters between the different years.

By 2024, however, clear differences emerged. Both RecOrgFert and NPK significantly improved soil organic carbon (1.64% and 1.87%, respectively) and organic matter content (2.93% and 3.22%), indicating enhanced nutrient cycling and organic matter turnover relative to the previous year. In contrast, HM maintained lower values, suggesting reduced

efficiency in sustaining soil organic reserves. Cation exchange capacity (CEC) declined under HM (16.5 meq/100 g), which may reflect limited contributions to soil colloidal stability, whereas control and NPK plots preserved higher CEC values. Interestingly, electrical conductivity (EC) increased notably under RecOrgFert in 2024 (0.91 dS/m), likely reflecting greater ionic activity and nutrient availability in the soil solution.

Overall, these results highlight that RecOrgFert and NPK were more effective in improving soil organic status and nutrient-holding capacity over time, while HM showed weaker effects, particularly on CEC and organic matter maintenance. The elevated EC under RecOrgFert also points to an enriched soil nutrient environment, potentially contributing to improved crop performance observed in the same period.

3.2.2. Plant Growth and Yield

NPK and RecOrgFert consistently enhanced wheat growth and productivity. In 2023 (Table 4), plant height peaked with NPK (105 cm) and RecOrgFert (101 cm), compared to 78 cm in unfertilized soil. Yield followed similar trends, with NPK (0.32 Kg/m^2) and RecOrgFert (0.29 Kg/m^2) far outperforming the control (0.22 Kg/m^2).

Table 4. Plant growth and grain biochemical parameters in the experiment in Italy (Apulia, 2023 and 2024).

	CTR	NPK	HM	RecOrgFert
		2023		
Plant height	78.0 ^{c}A ± 4.50	105.00 ^{a}A ± 8.30	84.0 ^{b}A ± 4.20	101.0 ^{a}A ± 7
seed/ear	36.0 ^{b}B ± 4.20	43.0 ^{a}A ± 5.80	37.0 ^{b}A ± 4.90	43.0 ^{a}A ± 6.10
Yield	0.22 ^{d}A ± 0.31	0.32 ^{a}A ± 0.45	0.24 ^{c}A ± 0.36	0.29 ^{b}A ± 0.38
Dry See	0.80 ^{a}A ± 0.045	0.80 ^{a}A ± 0.038	0.80 ^{a}A ± 0.041	0.80 ^{a}A ± 0.042
Proteins	10.50 ^{a}B ± 1.80	11.30 ^{a}A ± 2.20	10.80 ^{a}A ± 2.10	10.60 ^{a}A ± 1.95
Dry Gluten	7.00 ^{a}B ± 1.20	7.40 ^{a}B ± 1.45	6.80 ^{a}B ± 1.25	6.90 ^{a}B ± 1.30
β-carotene	0.52 ^{a}B ± 0.085	0.63 ^{a}B ± 0.12	0.65 ^{a}B ± 0.11	0.64 ^{a}B ± 0.095
TP	20.50 ^{c}A ± 0.88	22.41 ^{ab}A ± 0.95	22.25 ^{b}A ± 0.93	22.54 ^{a}A ± 1.02
TF	9.48 ^{c}B ± 0.41	19.76 ^{a}B ± 0.82	17.55 ^{b}A ± 0.73	18.31 ^{a}B ± 0.77
DPPH	33.99 ^{b}A ± 1.25	34.95 ^{b}A ± 1.29	36.54 ^{a}A ± 1.31	37.09 ^{a}A ± 1.34
ABTS^{+}	24.13 ^{b}A ± 1.08	23.88 ^{b}A ± 1.15	25.08 ^{ab}A ± 1.17	26.29 ^{a}A ± 1.21
		2024		
Plant height	60.3 ^{c}B ± 7.80	89.6 ^{a}B ± 7.40	72.5 ^{b}B ± 5.30	87.7 ^{a}A ± 6.80
seed/ear	38.0 ^{b}A ± 5.20	53.0 ^{a}A ± 7.30	35.0 ^{b}A ± 4.60	51.0 ^{a}A ± 6.90
Yield	0.20 ^{b}A ± 0.19	0.33 ^{a}A ± 0.47	0.26 ^{a}A ± 0.27	0.30 ^{a}A ± 0.22
Dry Seed	0.80 ^{a}A ± 0.052	0.80 ^{a}A ± 0.046	0.80 ^{a}A ± 0.044	0.80 ^{a}A ± 0.049
Proteins	14.50 ^{a}A ± 2.60	14.80 ^{a}A ± 2.85	14.80 ^{a}A ± 2.75	15.20 ^{a}A ± 3.10
Dry Gluten	12.10 ^{a}A ± 2.20	12.00 ^{a}A ± 2.35	11.70 ^{a}A ± 2.00	11.80 ^{a}A ± 2.10
β-carotene	2.23 ^{a}A ± 0.28	2.31 ^{a}A ± 0.32	2.30 ^{a}A ± 0.29	2.34 ^{a}A ± 0.35
TP	11.47 ^{c}B ± 0.52	11.09 ^{c}B ± 0.58	21.19 ^{a}A ± 1.01	20.53 ^{a}B ± 0.96
TF	10.55 ^{c}A ± 0.46	20.80 ^{a}A ± 0.94	16.87 ^{b}A ± 0.88	23.17 ^{a}A ± 1.01
DPPH	14.95 ^{c}B ± 0.85	22.93 ^{b}B ± 1.17	35.21 ^{a}A ± 1.39	35.25 ^{a}A ± 1.26
ABTS^{+}	24.82 ^{b}A ± 1.10	25.80 ^{b}A ± 1.13	27.44 ^{a}A ± 1.24	28.55 ^{a}A ± 1.19

CTR (control) = soil without fertilizer; NPK = nitrogen–phosphorus–potassium; HM = horse manure; RecOrgFert = bentonite sulfur + orange pomace. Plant height (cm); Seed/ear; Yield (Kg/m^2); Dry Seed (g/plant); Proteins (%); Dry gluten (% s.s.); β-carotene (mg/100 g). TP = total phenols (mg GAE g^{-1}); TF = total flavonoids (mg QE g^{-1}); DPPH = 2.2-difenil-1-picrilidrazile (% inhibition); ABTS^{+} = 2.2′-azino-bis-3-etilbenzotiazolin-6-solfonato (% inhibition). Data are the means of three replicates ± standard deviation. Different lowercase letters in the same row indicate significant differences (Tukey's test. $p \leq 0.05$). Different uppercase letters in the same column indicate significant differences (Tukey's test. $p \leq 0.05$) for the same parameters between the different years.

In 2024 (Table 4), plant height and seed/ear values declined in the control plot but remained high in NPK and RecOrgFert plots. Yield was the highest in NPK (0.33 Kg/m^2), followed by RecOrgFert (0.30 Kg/m^2) and HM (0.26 Kg/m^2).

Protein and gluten values improved significantly in 2024. Protein content in wheat fertilized with RecOrgFert reached 15.20%, with dry gluten content of11.80%. These results indicate superior nitrogen assimilation and grain quality under RecOrgFert. The β-carotene content in grain with RecOrgFert increased drastically from ~0.61 mg/100 g in 2023 to over ~2.30 mg/100 g in 2024 across all treatments.

3.2.3. Grain Biochemical Quality

In 2023 (Table 4), RecOrgFert led in TP (22.54 mg GAE/g), DPPH (37.09%), and $ABTS^+$ (26.29%). In 2024 (Table 4), HM ranked highest for DPPH (35.21%) and RecOrgFert retained high TP and antioxidant values. TF increased notably in NPK and RecOrgFert (20.80 and 23.17 mg QE/100 g).

4. Discussion

The results obtained in Greece demonstrated that RecOrgFert—a sustainable fertilizer composed of sulfur-bentonite and orange processing residues—significantly improved both soil health and wheat grain quality under Mediterranean conditions. In contrast to synthetic NPK, which is linked to soil degradation, greenhouse gas emissions, and water pollution [2,3], RecOrgFert enhanced soil organic matter and moisture retention while consistently increasing wheat protein and gluten content. These effects are largely attributable to its sulfur component, a limiting nutrient in many Mediterranean soils that is essential for the biosynthesis of sulfur-containing amino acids (e.g., methionine and cysteine) and for efficient nitrogen assimilation, both of which support protein accumulation [28,29]. The addition of orange-derived organic matter further boosted RecOrgFert's effectiveness, as citrus residues are rich in polyphenols, flavonoids, and soluble carbon that stimulate microbial activity and serve as precursors for antioxidant biosynthesis [30]. Accordingly, RecOrgFert-treated grains showed consistently higher phenolic content, β-carotene levels, and antioxidant activity (DPPH, $ABTS^+$).

Pearson correlation analysis across the 2023–2024 trials provided further evidence of RecOrgFert's capacity to create a rhizosphere optimized to produce functional foods. The 2023 data revealed balanced interactions between nutrient availability and plant growth, leading to simultaneous improvements in yield and nutritional quality, while the 2024 findings confirmed these patterns, showing synchronized nutrient absorption and strong positive correlations among bioactive compounds. The progressive improvements observed between the two years suggest long-term benefits through structural changes in soil quality. Importantly, the consistency of results across different seasonal conditions underscores RecOrgFert as a reliable and sustainable fertilization strategy. These findings are in line with previous studies reporting that organic and organo-mineral fertilization enhances microbial diversity and nutrient cycling, with downstream effects on crop health and quality [31–33]. Overall, the combined contribution of sulfur and bioactive-rich citrus residues in RecOrgFert improved both soil biochemistry and grain nutritional quality, confirming its promise as a waste-derived fertilizer that can support agroecological transition strategies in Mediterranean drylands [6–8].

Comparable outcomes were observed in Southern Italy, where RecOrgFert not only enhanced wheat yield and grain quality but also improved key soil fertility parameters in a region prone to organic matter depletion and low microbial activity [5,34]. As in Greece, sulfur facilitated nitrogen assimilation and protein synthesis, leading to higher grain protein and gluten levels [28], while citrus residues stimulated microbial activity and contributed

to greater β-carotene and phenolic accumulation [8,35,36]. RecOrgFert also demonstrated consistency in yield and quality across years, suggesting resilience to seasonal variability. The Italian correlation analysis confirmed its superior effectiveness: in 2023, RecOrgFert fostered positive relationships between soil ΔpH and antioxidant activity, as well as optimization of Δβ-carotene profiles, indicating synergistic coordination between nutrient absorption and bioactive compound synthesis. By 2024, these effects had strengthened, with clearer patterns of carotenoid optimization and more robust inter-nutrient correlations, highlighting progressive improvements not seen with conventional treatments.

Taken together, the results from both sites confirm RecOrgFert's dual role in enhancing soil fertility and boosting crop nutritional value, with effects that consolidate over time. The agreement between Greek and Italian trials underscores its reliability across contrasting Mediterranean environments, supporting its application as a practical and resilient fertilization strategy. Consistent with recent literature, these findings emphasize the potential of organic and organo-mineral amendments to improve soil physicochemical properties, microbial diversity, and ultimately the functional quality of food crops [31–38]. By integrating sulfur and bioactive-rich residues into a single formulation, RecOrgFert emerges as a particularly effective approach to producing high-value, nutrient-dense grains while contributing to the sustainability of Mediterranean agroecosystems.

5. Conclusions

This study provides compelling evidence that RecOrgFert is a highly effective and sustainable solution for Mediterranean wheat systems. Across two growing seasons and two agro-ecological contexts (Greece—Central Macedonia and Italy—Apulia), RecOrgFert demonstrated the ability to enhance soil fertility, increase plant productivity, and improve grain nutritional and functional quality. Unlike synthetic fertilizers such as NPK, RecOrgFert promoted organic matter accumulation and improved soil chemical balance (pH, EC, WC). These improvements translated into agronomic outcomes, including higher yields, improved nitrogen use efficiency, and significant enhancement of protein, gluten, antioxidant, and β-carotene content in wheat grain. RecOrgFert is not merely a viable alternative to mineral fertilizers—it is a strategic resource for advancing sustainable, circular, and climate-resilient agriculture in the Mediterranean and beyond. Future research should build on the present findings to consolidate RecOrgFert's role as both a scientific innovation and a practical solution at the nexus of productivity, sustainability, and food security. Future research prospects and considerations should focus on long-term trials across different soil types, climates, and crop systems to assess its capacity to restore degraded soils. Mechanistic studies on soil–microbiome interactions are also needed to provide deeper insights into how citrus-derived organic fractions stimulate beneficial microbial consortia and influence nutrient cycling.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app151810292/s1, Table S1: Seasonal Climate in Thessaloniki (2023/2024 Overview, based on averages and reported events). Table S2: Seasonal Climate in Foggia (Apulia, Italy—2023/2024 Overview based on averages and reported events). Figure S1: (a) Experimental field Apulia south Italy, control (Red), NPK (Green), RecOrgFert (Yellow), and horse manure (Blue). (b) experimental field Thessaloniki Greece, Control (green), NPK (blue), RecOrgFert (Yellow), and horse manure (violet). Figure S2: Pearson correlation matrix illustrating the relationships between soil and grain parameters for the experiment in Greece 2023. Figure S3: Pearson correlation matrix illustrating the relationships between soil and grain parameters in Greece 2024. Figure S4: Pearson correlation matrix illustrating the relationships between soil and grain parameters in Italy 2023. Figure S5: Pearson correlation matrix illustrating the relationships between

soil and grain parameters in Italy 2024. Table S3: Chemical Characteristics of Soils in Greece and Apulia before starting the experiments (T0).

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Abbreviations

The following abbreviations are used in this manuscript:

CTR	Control, soil without fertilizer
NPK	Nitrogen–phosphorus–potassium
HM	Horse manure
WC	Water content
EC	Electrical conductivity
OC	Organic carbon
TotN	Total nitrogen
C/N	Carbon–nitrogen ratio
OM	Organic matter
CEC	Cation exchange capacity
TP	Total phenols
TF	Total flavonoids
DPPH	2,2-difenil-1-picrilidrazile
$ABTS^{+}$	2,2′-azino-bis-3-etilbenzotiazolin-6-solfonato

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