

Article

Exploring Dry Salmon Sludge as an Organic Nitrogen Source for Hazelnut (*Corylus avellana* L.) Orchard

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Abstract

The rapid expansion of the salmon industry has generated increasing amounts of waste sludge with negative environmental impacts. Sustainable alternatives, such as using stabilized sludge in agriculture, are needed to mitigate these effects. At the same time, fruit production has grown globally, with hazelnut (*Corylus avellana* L.) emerging as a crop of high economic importance. However, the effect of salmon sludge application on hazelnut orchards is poorly understood. This study evaluated the application of thermally stabilized fish farming sludge (DS) compared with a slow-release mineral fertilizer (MF) in two hazelnut varieties, ‘Barcelona’ (B) and ‘Tonda di Giffoni’ (TDG). Growth parameters including trunk cross-sectional area (TCSA), cumulative growth, shoot growth rate, leaf mass area (LMA) and chlorophyll index (SPAD), as well as soil physicochemical properties and enzymatic activities (fluorescein diacetate, β -glucosidase, acid phosphatase) were assessed. No significant differences ($p > 0.05$) in physiological parameters were found between DS and MF. However, the DS application increased soil pH by up 18%, electrical conductivity by ~48% at peak values, and enzymatic activities by 44% (acid phosphatase in B variety), 38% (β -glucosidase in TDG) and 169% (FDA in TDG), suggesting a great organic matter contribution and enhanced soil metabolic activity. Additionally, the B variety showed superior physiological performance, while TDG exhibited higher enzymatic activity. Overall, these findings provide a preliminary assessment of DS as a sustainable supplement to mineral nitrogen fertilization in hazelnut orchards, supporting both soil quality improvement and circular economy strategies in agriculture and aquaculture.

Keywords: salmon sludge; mineral fertilizer; waste revalorization; circular economy; *Corylus avellana*



Academic Editor: Tongbin Zhu

Received: 5 December 2024

Revised: 14 October 2025

Accepted: 13 November 2025

Published: 24 November 2025

Citation: Cayunao, S.; Pérez-San Martín, A.; Jorquera-Fontena, E.; Huerta-Mendoza, V.; Tortosa, G.; Alvear, M.; Ortiz, J.; Oladele, S.O.; Curaqueo, G. Exploring Dry Salmon Sludge as an Organic Nitrogen Source for Hazelnut (*Corylus avellana* L.) Orchard. *Nitrogen* **2025**, *6*, 110. <https://doi.org/10.3390/nitrogen6040110>

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1. Introduction

Aquaculture production worldwide is expanding to meet the growing demand for farmed fish, making it a key industry in countries such as Norway, China, and Chile [1]. However, this growth has raised environmental concerns, mainly due to increased waste generation linked to the intensification of systems such as recirculating aquaculture systems (RAS). These systems reuse approximately 95% of water but accumulate sludge, primarily composed of feces and uneaten food, which presents challenges in disposal and management due to its high moisture content [2,3]. This sludge is often disposed of by direct dilution into the sea, municipal wastewater systems, or landfills [4,5]. The reuse of aquaculture sludge in agriculture offers a sustainable approach to reducing environmental pollution, thanks to its high levels of nutrients and organic matter [4]. Reported values include available nitrogen (N) ranging from 539 to 3122 mg kg⁻¹, total phosphorus (P) from 8.5 to 75.5 g kg⁻¹, available potassium (K) from 71 to 173 mg kg⁻¹, and organic matter content between 47% and 56% [6]. This practice promotes circular economy principles by adding value to agricultural systems, improving sustainability, and reducing dependence on synthetic mineral fertilizers [3,6].

In parallel, fruit cultivation has experienced significant global growth, with hazelnut (*Corylus avellana* L.) emerging as a crop of economic interest. Turkey leads worldwide production with 684,000 tons, followed by Italy, the United States, and Chile, which have over 36,300 hectares of cultivated area and a production of 65,646 tons in shell [7,8]. In Chile, the 'Barcelona' (60%) and 'Tonda di Giffoni' (40%) varieties are the most widely cultivated, driven by demand for both direct consumption and industrial use, especially in the chocolate industry, with prices between US\$ 4–5 kg⁻¹ [9]. Despite considerable progress in hazelnut cultivation, it is crucial to adapt fertilization and soil management practices toward more environmentally friendly options, particularly to meet the increasing demand for organic products [10,11]. In this context, applying stabilized sludge from aquaculture offers a viable alternative to reduce synthetic mineral fertilizer use, providing nutrients and improving soil biological activity [12]. This research aims to assess the effects of stabilized fish farming sludge on physiological responses and soil properties associated with the hazelnut varieties Barcelona and Tonda di Giffoni, positioning it as a sustainable alternative to nitrogen mineral fertilizers. Additionally, it aims to promote sustainable management practices for hazelnut production, aligning with the growing demand for organic and sustainable products among consumers. This study represents an initial step toward integrating aquaculture residues into fruit production systems, reinforcing the principles of the circular economy and sustainable agriculture.

2. Materials and Methods

2.1. Experimental Site

The study was conducted during the 2022–2023 season at the Pillanlelbún Experimental Station, Universidad Católica de Temuco (38°39'06" S; 72°26'56" W). The climate is Mediterranean (Csb), with wet winters (June to August) and dry summers (December to March) [13]. The Pillanlelbún Meteorological Station recorded a maximum average temperature of 25.9 °C in February, a minimum average temperature of 2.5 °C in May, and the annual rainfall averages 1293 mm (Watchdog Weather Station, Spectrum Technologies, Inc. Aurora, Pittsburgh, PE, USA). The site terrain is flat, with a <2% slope, and the soil is an Andisol, a volcanic ash-derived soil (Temuco series, Typic Hapludands) [14]; moderately deep, Donewith a silt loam surface texture, moderate permeability, and drainage [15]. The Temuco soil (0–20 cm depth) exhibits a high organic matter content (18%), moderate available P (11 mg kg⁻¹), moderate pH acid (pHw 5.77), and a low aluminum saturation of 1.02%.

2.2. Plant Material

The plant material consisted of unproductive three-year-old *Corylus avellana* varieties Barcelona (B) and Tonda Di Giffoni (TDG), planted with a spacing of 5×4 m in north–south-oriented rows. Pest control was performed chemically using 20 mL ha^{-1} of bifenthrin (FMC Corporation, Philadelphia, PA, USA), following the technical recommendations of the export fruit industry.

2.3. Treatments

Thermally stabilized fish farming sludge was obtained from the *Salmo salar* culture in a freshwater recirculation system (RAS) at “Compañía Salmonífera Dalcahue Ltda, Piscicultura San Patricio” located in Vilcún, La Araucanía Region, Southern Chile ($38^{\circ}38'15'' \text{ S}$, $72^{\circ}05'46'' \text{ W}$). The physicochemical characterization of the dry sludge was described by San-Martín et al. [12]. For the experiment, 20 representative trees were randomly selected from a total of 50 trees per row in two orchard rows ($n = 20$ per treatment) to apply stabilized dry sludge (DS) as a cover, and compared to trees supplied with Basacote® Plus (CompoExpert. Santiago, Chile), a slow-release commercial mineral fertilizer (MF) (Table 1). The doses for both DS and MF were equivalent to $15 \text{ units of N ha}^{-1}$ applied on 24 September 2022.

Table 1. Chemical analysis of mineral fertilizer and dry sludge.

Parameters	Mineral Fertilizer	Dry Sludge
Total N (%)	16.0 ± 0.4	6.4 ± 0.10
NO_3^- (mg kg^{-1})	7.4 ± 1.8	292 ± 2.65
NH_4^+ (mg kg^{-1})	8.6 ± 0.2	2608 ± 34
Total P_2O_5 (mg kg^{-1})	8.0 ± 0.3	73.05 ± 21
Total K_2O (mg kg^{-1})	12.0 ± 0.7	1.8 ± 0.1
Total B (mg kg^{-1})	0.02 ± 0.001	10 ± 0.6
Total Cu (mg kg^{-1})	0.05 ± 0.001	24 ± 0.3
Total Fe (mg kg^{-1})	0.40 ± 0.05	290 ± 5.70
Total Mn (mg kg^{-1})	0.06 ± 0.001	60 ± 1.80
Total Zn (mg kg^{-1})	0.02 ± 0.001	812 ± 3.7

Values represent mean $\pm$ standard deviation ($n = 3$).

2.4. Physiological Parameters

Leaf mass per area (LMA) analysis was performed 28 and 84 days after the application (daa) of the dry sludge. Three trees per row were measured ($n = 6$ per treatment), considering five mature leaves per plant. Leaves were scanned, and their area was calculated using an image analysis program developed in our laboratory [16], validated according to the recommendations of O’Neal et al. [17]. The leaves were then dried at 60°C for 48 h to determine dry mass. LMA values were calculated using Equation (1) and expressed as g cm^{-2} .

$$\text{LMA} = \frac{\text{Dry mass}}{\text{Leaf area}} \quad (1)$$

The chlorophyll index was evaluated in SPAD units using a chlorophyll meter (Apogee MC100, Apogee Instruments Inc., Logan, UT, USA), as described by de Souza et al. [18], with some modifications. Measurements were performed at 14-day intervals (28, 42, 56, 70, 84, 98, and 112 daa) from 11:00 to 13:00 h on cloudless days. For readings, two representatives and the exact size of sun-exposed leaves were taken from shoots of ten randomly selected trees per row ($n = 20$ per treatment). Two readings were made in the mid-section of each leaf, and the values were averaged.

The accumulated shoot growth was monitored using two main shoots per plant ($n = 20$ per treatment), following the methodology described by Giovannini et al. [19].

Determinations were performed every 15 days at 28, 42, 56, 70, 84, 98, and 112 daa, measuring from the base to the end of the shoot with metric tape.

The absolute growth rate (AGR) was estimated from cumulative shoot growth using Equation (2) [20]:

$$\text{AGR} = \frac{(M2 - M1)}{(\text{n days})_{M2} - (\text{n days})_{M1}} \quad (2)$$

where AGR is the absolute growth rate, M2 is the day two measurement of cumulative shoot growth, M1 is the day one measurement of shoot growth, and n days corresponds to the difference in days between measurement one and measurement two and is expressed as cm d^{-1} .

The trunk cross-sectional area (TCSA, cm^{-2}) was measured in each tree ($n = 20$ per treatment) at 0, 56, and 112 daa of the sludge. This parameter was calculated by measuring the trunk perimeter (C) of the trees at 20 cm from the ground, according to Equation (3):

$$\text{TCSA} = \frac{(C)^2}{4\pi} \quad (3)$$

2.5. Soil Physicochemical and Biochemical Parameters

Soil physicochemical parameters, including pH and electrical conductivity (EC), were monitored in each experimental unit ($n = 20$ per treatment) every 14 days at 28, 42, 56, 70, 84, 98, and 112 daa. These parameters were analyzed in situ at 0–5 cm depth in triplicate using a portable soil pH and EC meter (Hanna Instruments, Woonsocket, RI, USA).

Soil enzyme activity was measured at both the start and end of the assay, using composite soil samples around the root zone (consisting of four subsamples) at 0–5 cm depth from three random experimental units in the row (in three replicates per treatment, $n = 9$). Samples were immediately placed in polyethylene bags, kept at 4 °C, and transported to the laboratory for analysis. To account for moisture, a dry weight factor was calculated by dividing the dry mass by the wet mass and multiplying by the concentration obtained in each analysis. Fluorescein diacetate (FDA) activity was determined according to Alvear et al. [21], with some modifications, using 1 g of wet soil, 10 mL of sodium phosphate buffer (60 mmol L^{-1} , pH 7.6), and 100 μL of FDA substrate (2000 mg L^{-1} in acetone). Samples were incubated at 25 °C for 1 h, then 10 mL of acetone was added to stop the reaction, followed by filtration. The activity was quantified using UV-Vis spectroscopy at 490 nm, with a reagent blank. Results were expressed as $\mu\text{g Fluorescein g}^{-1} \text{ h}^{-1}$. β -Glucosidase activity was measured following the method of [18], adding 4 mL of MUB buffer (pH 6.0), 1 mL of p-nitrophenyl- β -D-glucopyranoside (25 mM), and 2 mL of water to 1 g of wet soil. After 1 h of incubation at 37 °C, 1 mL of CaCl_2 (0.5 M) was added, and then the samples were filtered with Tris buffer (pH 12.0). Absorbance was measured at 400 nm, and results were expressed as $\mu\text{g p-nitrophenyl g}^{-1} \text{ h}^{-1}$. Acid phosphatase activity was assessed similarly, using MUB buffer (pH 5.5) and p-nitrophenyl phosphate (15 mM). After 1 h of incubation, CaCl_2 (0.5 M) was added, and samples were filtered with NaOH (0.5 M). Absorbance was measured at 400 nm, and results were expressed as $\mu\text{g p-nitrophenyl g}^{-1} \text{ h}^{-1}$.

2.6. Statistical Analysis

The results obtained were evaluated using a normality test according to the Shapiro–Wilk method [22] and a homogeneity of variance analysis following Levene's test [23]. A *t*-test was used to identify significant differences between treatments. A one-way ANOVA was performed to compare the same treatment at different measurement times. Subsequently, a post hoc analysis was conducted using the Tukey HSD test for

multiple mean comparisons. The data analysis was carried out using JASP software 0.19.3 with a 95% confidence level.

3. Results and Discussion

The LMA showed no significant differences between sludge application (DS) and mineral fertilization (MF), indicating that the biomass investment per unit of leaf area was unaffected by the treatment (Figure 1A,B). Poorter et al. [24] reported that LMA is closely associated with the daily photosynthesis rate per unit of leaf area, suggesting that replacing mineral fertilization with sludge may not affect carbon assimilation under our experimental conditions. On the contrary, the use of sludge provides soil nutrition comparable to that of conventional mineral fertilizer [25]. In our study, the stability of LMA across treatments indicates that DS application did not limit photosynthetic potential or biomass allocation, even under Andisol conditions characterized by high organic matter and P-fixation capacity. This observation aligns with Catoni et al. [26], who described LMA as a conservative indicator, more affected by genotype and environmental factors than by fertilization type. Furthermore, the slight temporal decline in LMA values may reflect natural leaf senescence rather than nutrient limitation, as also observed by Rovira et al. [27] in hazelnut cultivars under Mediterranean climates. LMA values also tended to decrease over time, possibly due to leaf senescence and reduced tissue density [28,29]. The lower variation observed in B-DS at 84 daa compared with TDG-DS indicates a varietal effect, where genetic differences between hazelnut cultivars influence trait stability and variability [30].

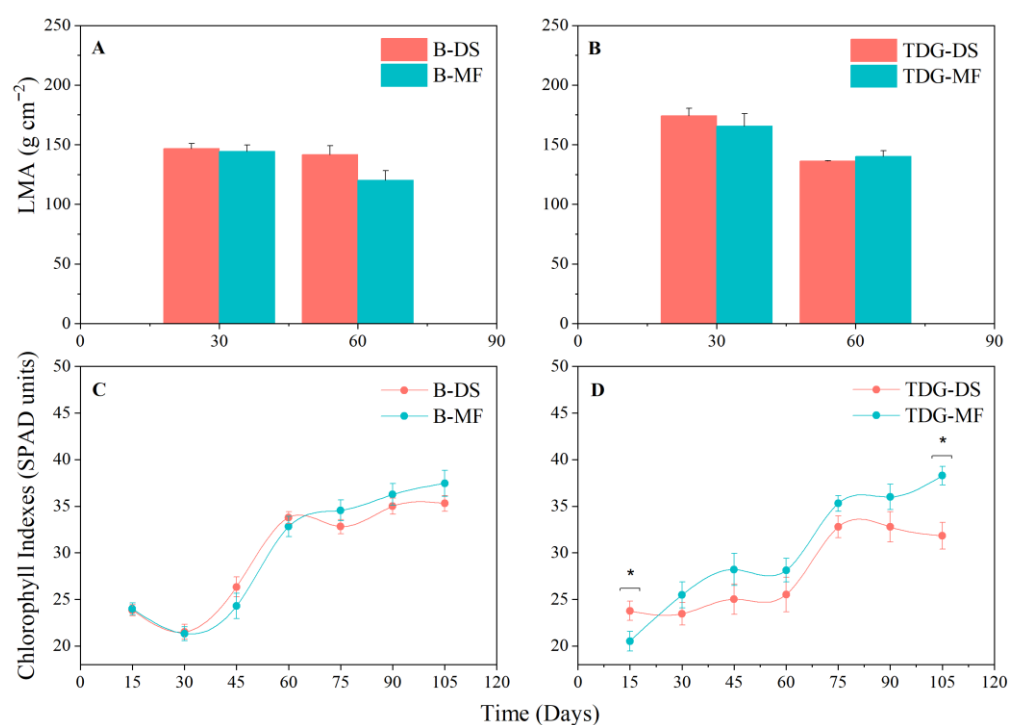


Figure 1. Leaf mass per area (A,B) and SPAD units (C,D) for Barcelona and Tonda Di Giffoni varieties at different times. Asterisks indicate significant differences between treatments for the same time according to Student's *t*-test ($p \leq 0.05$). Results indicate mean $\pm$ standard deviation (LMA $n = 6$; SPAD $n = 20$).

Similarly, leaf chlorophyll index (SPAD) showed no significant differences between treatments at most measurement dates (Figure 1C,D). The lack of significant SPAD differences between DS and MF treatments throughout most sampling dates suggests that nitrogen supplied by sludge mineralization was sufficient to maintain chlorophyll content. This behavior is consistent with Fiorentini et al. [31], who showed that gradual N release

from organic sources sustains stable SPAD values comparable to synthetic fertilizers. The slight SPAD reduction at 112 daa under DS may be related to the slower release of mineral N fractions, as reported by Braun et al. [32] for hybrid hazelnuts fertilized with slow-release N sources. Furthermore, SPAD increases over time ($\approx 40\%$) are typical of leaf maturation and chlorophyll accumulation under optimal N nutrition, confirming that sludge-derived N became bioavailable during the vegetative period. Other studies in fruit trees and prairies have shown similar responses when replacing mineral N with stabilized or composted sludge, reinforcing its suitability as a nitrogen source in perennial systems [33,34]. The only exception occurred at 112 daa in TDG, where sludge application appeared to reduce SPAD values (Figure 1C,D), possibly reflecting the nutrient-release dynamics of the commercial fertilizer tested here.

In contrast to LMA, SPAD values varied significantly over time, increasing by about 40% from 28 to 112 daa for both varieties. A similar trend was reported by Rovira et al. in hazelnuts [27], although the values in the present study were lower, likely due to differences in genotype. Although SPAD measurement is recognized as a proper eco-physiological parameter for monitoring physiological and nutritional status [35,36], its application in hazelnuts remains limited, particularly under field conditions [37].

As expected, cumulative shoot growth followed a sigmoidal pattern for both varieties, with values approximately 30% higher in B than in TDG at the plateau (Figure 2A,B). This result is consistent with previous evidence reporting greater vigor in the B variety compared to TDG [10,30,38,39]. The evaluated treatments did not show statistically significant differences in shoot growth; however, a trend toward higher values was observed in B-DS compared with B-MF after 42 daa, although this trend did not influence the overall growth rate (Figure 2C,D).

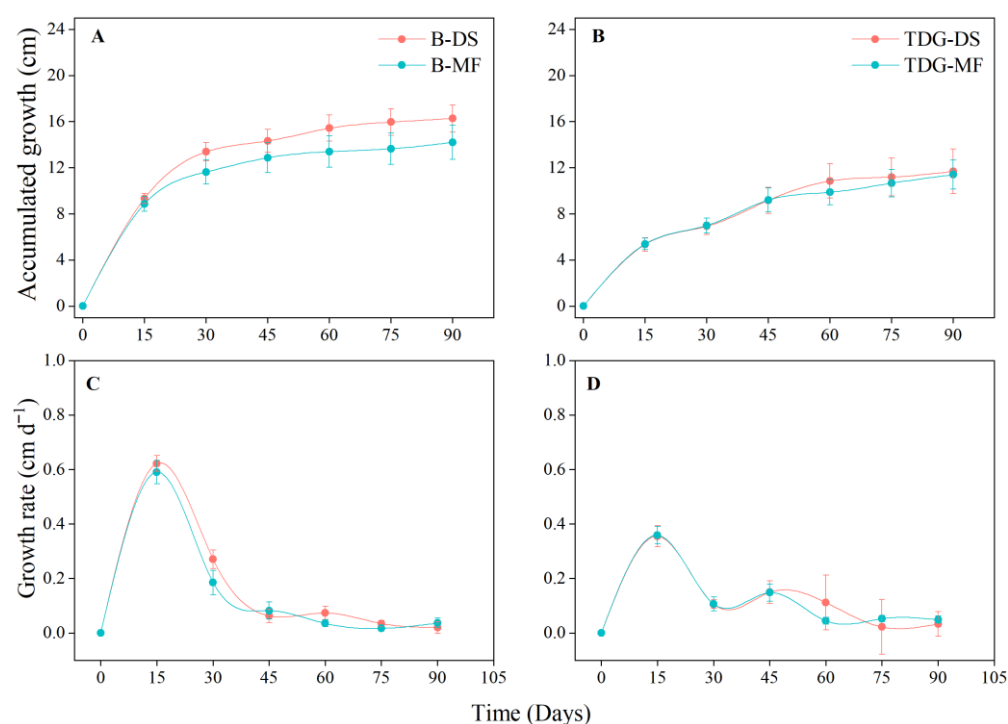


Figure 2. Accumulated shoot growth (A,B) and absolute growth rate (C,D) for Barcelona and Tonda Di Giffoni varieties at different times. Asterisks indicate significant differences between treatments for the same time according to Student's *t*-test ($p \leq 0.05$). Results indicate mean $\pm$ standard deviation ($n = 20$).

The TCSA increased over time for both varieties, with statistically significant differences between treatments detected at 112 daa for TDG (Figure 3A,B). Applying organic

fertilizers derived from sewage sludge significantly improves soil nutrient content (nitrogen, phosphorus, potassium, and organic matter) and water relations, indirectly stimulating secondary growth in hazelnut orchards. This nutrient enrichment leads to enhanced vegetative growth, which is closely linked to increases in trunk cross-sectional area over time [40]. Previous studies have demonstrated that organic fertilizers based on treated sludge enhance soil cation exchange capacity and microbial-driven nutrient cycling, leading to improved trunk growth and yield in fruit trees [25,41]. The consistency of our results with those of Grau [38] in Chilean hazelnuts further supports that organic sources can substitute part of mineral N without penalizing growth. The observed response also highlights the relevance of slow nutrient release and improved soil biological activity for maintaining a continuous nutrient supply in perennial systems.

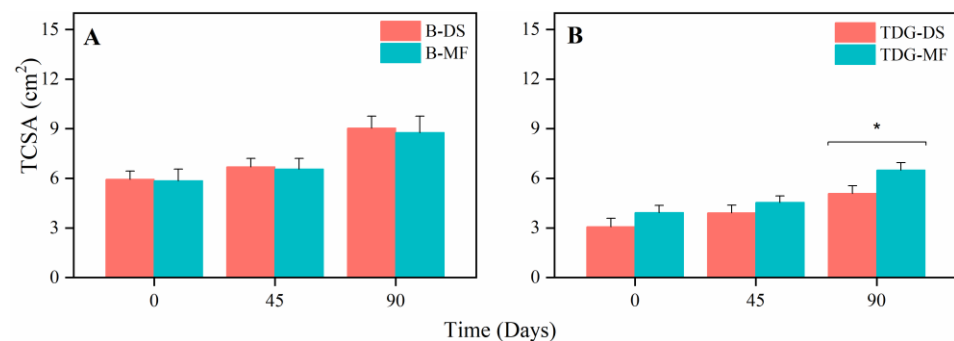


Figure 3. Trunk cross-sectional area for varieties Barcelona (A) and Tonda Di Giffoni (B) at different times. Asterisks indicate significant differences between treatments for the same time according to Student's *t*-test ($p \leq 0.05$). Results indicate mean $\pm$ standard deviation ($n = 20$).

Soil pH dynamics are shown in Figure 4A,B. In both varieties, pH values were significantly higher under dry sludge application compared with mineral fertilization. In B, initial values were 7.38 ± 0.13 for B-DS and 5.15 ± 0.10 for B-MF. B-DS decreased significantly to 4.98 ± 0.10 at 70 daa, then stabilized near neutrality (6.56 ± 0.14) by 112 daa. In contrast, B-MF dropped to 4.44 ± 0.05 at 70 daa and reached 5.55 ± 0.07 at 112 daa. The TDG variety followed a similar trend, with initial values of 7.43 ± 0.07 in TDG-DS and 5.17 ± 0.07 in TDG-MF. TDG-DS declined to 5.13 ± 0.16 at 70 daa before increasing to 6.21 ± 0.07 at 112 daa, while TDG-MF showed less variation, ending at 5.54 ± 0.09 at 112 daa. In this context, the initially high pH values observed under DS application may be attributed to the lack of sludge stabilization. Previous studies have reported that composting sewage sludge helps regulate its pH, maintaining values closer to neutrality [42,43]. The subsequent decrease in pH following DS application could be associated with the release of NH_4^+ during sludge mineralization in the soil [32–34,44]. Research by Cardoso et al. [43], Naserian et al. [42], Wong et al. [45], and de Soto et al. [46] showed similar pH trends in Andisols amended with composted or thermally stabilized sludge. In turn, nitrification of this compound may contribute to soil acidification by releasing H^+ ions [35,36,47]. Later increases in pH may reflect ongoing stabilization during sludge mineralization and the accumulation of NH_3 [48,49]. This process could explain the higher pH values observed at 112 daa in both varieties, a potentially beneficial effect that may improve soil conditions and nutrient solubility in volcanic soils [34,50]. In contrast, the lower pH values under MF likely reflect the ammoniacal nitrogen content of the fertilizer and its controlled-release characteristics [40,41]. These pH shifts are agronomically relevant for Andisols, where neutralization can enhance P availability and reduce Al^{3+} toxicity, thereby improving nutrient uptake efficiency and microbial activity. However, the use of ammoniacal fertilizers leads to a decrease in pH [51,52].

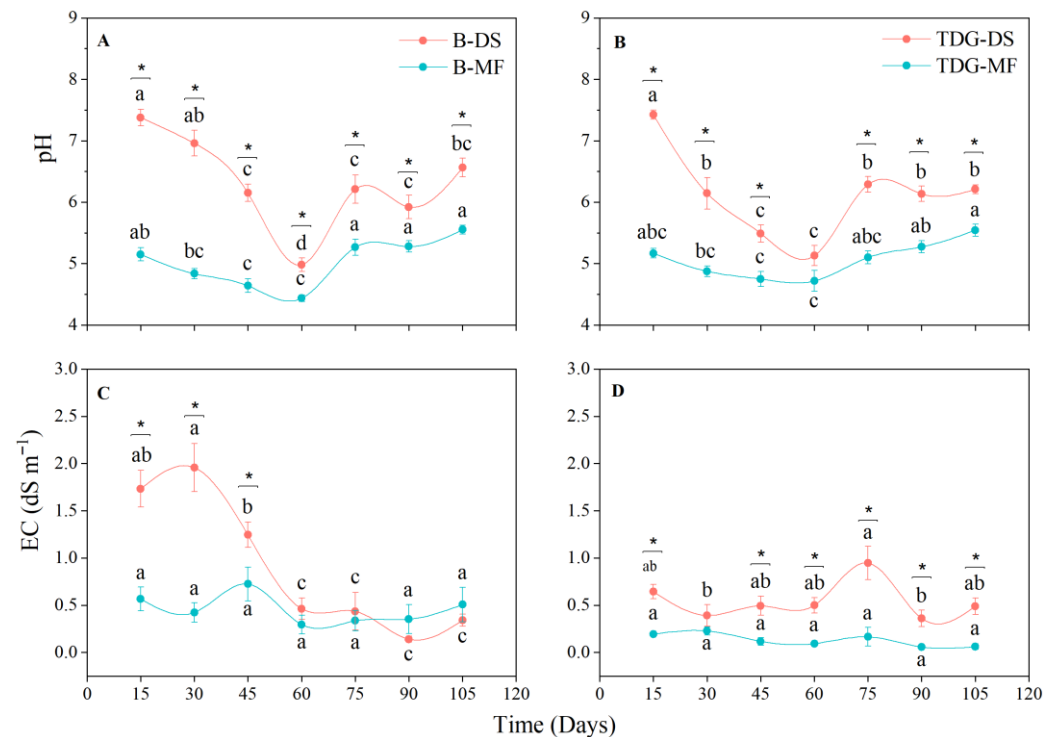


Figure 4. Changes in pH (A,B) and electrical conductivity (C,D) for Barcelona and Tonda Di Giffoni varieties at different times. Asterisks indicate significant differences between treatments for the same time according to Student's *t*-test ($p \leq 0.05$). Different letters indicate differences for the same treatment at different times according to Tukey's method ($p \leq 0.05$). Results indicate mean $\pm$ standard deviation ($n = 20$).

The results of the electrical conductivity (EC) analyses are presented in Figure 4C,D. In the B variety, the B-DS treatment showed an initial EC of 1.73 ± 0.19 dS m⁻¹, which increased slightly to 1.96 ± 0.25 dS m⁻¹ at 42 daa, with no significant differences. From 56 daa onward, EC declined significantly, reaching values similar to those of B-MF and stabilizing at 0.34 ± 0.06 dS m⁻¹ by 112 daa. Conversely, B-MF remained more stable throughout the experiment, starting at 0.57 ± 0.12 dS m⁻¹, peaking at 0.72 ± 0.17 dS m⁻¹ at 56 daa, and ending at 0.50 ± 0.18 dS m⁻¹. No significant differences were found between treatments at the final measurement, suggesting that EC levels under DS stabilized in the soil after 70 daa. The TDG variety exhibited lower EC values than B. In TDG-DS, EC increased from 0.64 ± 0.07 dS m⁻¹ initially to 0.95 ± 0.17 dS m⁻¹ at 84 daa, before decreasing to 0.49 ± 0.08 dS m⁻¹ at 112 daa. TDG-MF showed minimal variation, ranging from 0.20 ± 0.02 dS m⁻¹ at 28 daa to 0.06 ± 0.03 dS m⁻¹ at 112 daa. Significant differences between treatments were detected in TDG but not in B.

According to Sanchez-Monedero et al. [53], EC is primarily determined by the nature and composition of the material, reflecting both salt concentration and the presence of ammonium or nitrate ions formed during stabilization, which is in agreement with other research [43,44,54,55]. The initially higher EC values observed under DS application likely reflect the abundance of soluble ions and exchangeable bases such as Na⁺, K⁺, Mg²⁺, and Ca²⁺, as indicated in the chemical characterization of the sludge reported in a previous work of Pérez-San Martín et al. [12].

Inorganic nitrogen concentration and the mineralization process can also influence soil ion dynamics [32,46,47,56]. Conversely, lower EC values may be associated with salt leaching caused by irrigation or excessive soil moisture [57]. Similar trends were reported by Delgado et al. [58], who initially observed high EC values that declined substantially over time, resulting in stabilized salinity levels [59].

To further evaluate soil quality and stabilization under DS application, enzymatic activity was assessed through the fluorescein diacetate hydrolysis (FDA). This method estimates total microbial activity by measuring intra- and extracellular enzymes such as esterases, proteases, and lipases [51–53,60,61]. Both varieties exhibited a significant increase in FDA activity at 60 daa under DS treatment, reaching 5.9 ± 0.4 and $13.2 \pm 1.1 \mu\text{g F g}^{-1} \text{h}^{-1}$ for B and TDG, respectively. In contrast, MF application produced only slight increases, with maximum values of 4.0 ± 0.4 and $4.9 \pm 0.3 \mu\text{g F g}^{-1} \text{h}^{-1}$ for B and TDG, respectively. These results agree with previous findings [62,63], which indicates that organic matter and nutrient additions stimulate microbial metabolism. According to Liu et al. [63] and Elbl et al. [64], FDA activity is considered a reliable soil quality indicator, as it responds to organic amendments and contaminants such as heavy metals and pesticides [55–57], reflecting microbial stimulation following organic amendment addition, driven by increases in carbon availability and enzyme synthesis. The significant difference between DS and MF treatments, particularly at 60 daa, confirms that sludge application activates soil microbial metabolism beyond simple nutrient effects [65,66]. Such findings align with Sánchez-Monedero et al. [61], who showed that organic amendments boost microbial respiration and enzymatic activity even in high-OM soils.

The β -glucosidase activity results are shown in Figure 5C,D for B and TDG, respectively. This extracellular enzyme is a key indicator of soil quality and microbial activity due to its role in the carbon cycle [67,68]. The results followed a similar pattern to FDA activity, with higher values under DS application: 44.5 ± 1.5 and $47.0 \pm 2.33 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ for B and TDG, respectively. No significant differences were detected in B at 60 daa compared with MF, whereas TDG showed a notable increase, reaching $33.8 \pm 2.2 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ (a 66.3% rise compared with 62.4% in TDG-DS). β -glucosidase activity is known to be sensitive to pH, salinity, and heavy metal concentrations, which reinforces its use as an indicator of soil quality [69,70]. The increase in β -glucosidase activity under DS application, confirming a positive effect on soil organic matter turnover. This observation agrees with Zhang et al. [68] and Adetunji et al. [71], who found that organic amendments stimulate β -glucosidase activity by enhancing microbial substrate availability and promoting soil aggregation. Enhanced β -glucosidase activity also reflects improved C sequestration potential, as microbial degradation of cellulose releases labile C fractions that sustain soil respiration. In the same way, previous studies [71,72] also report that β -glucosidase activity is enhanced by organic amendments such as sewage sludge compared with synthetic fertilizers.

Acid phosphatase activity results for B and TDG are presented in Figure 5E,F. This extracellular enzyme catalyzes the hydrolysis of phosphoester bonds in organic matter, releasing orthophosphate available for plants [63,64,73]. Similarly to FDA and β -glucosidase, acid phosphatase activity increased under DS application in both varieties. In B, activity rose by 77.2% and 36.1%, reaching 75.5 ± 2.8 and $52.5 \pm 2.9 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ at 60 daa for DS and MF, respectively. In contrast, TDG exhibited increases of 54.8% and 69.6%, reaching 87.8 ± 4.3 and $75.6 \pm 6.6 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ for DS and MF, respectively. Increased acid phosphatase activity under DS treatment indicates enhanced P mineralization and microbial turnover. Similar trends have been observed by Margalef et al. [74] and Bünemann [75], demonstrating that organic inputs stimulate phosphatase synthesis under moderate P availability. In the same sense, the main factors influencing phosphatase activity include reduced microbial and plant dependence on organic P mineralization when inorganic P availability increases [74,76], the chemical form of organic P, microbial community composition, and physicochemical properties such as pH and temperature [75,77]. Additionally, N and P fertilization can interact with phosphatase activity, sometimes reducing enzyme activity in soils rich in natural P [75]. These findings suggest that nitrogen availability may

be more relevant than phosphorus, depending on the applied ratios, types of soil, and agroecosystems studied [69–71].

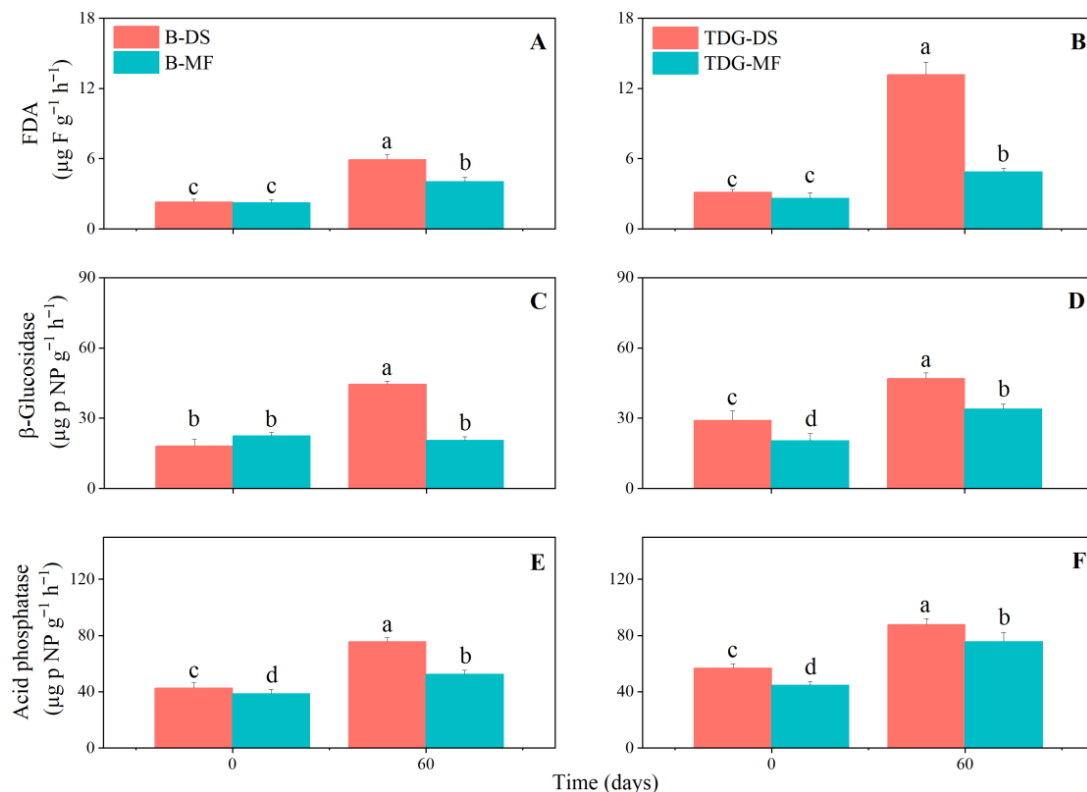


Figure 5. Dynamics of enzymatic activity. FDA (A,B), β -Glucosidase (C,D), and acid phosphatase (E,F) for Barcelona and Tonda Di Giffoni varieties. Different letters indicate significant differences between treatments at different times according to Tukey's method ($p \leq 0.05$). Results indicate mean $\pm$ standard deviation ($n = 9$).

Overall, the enzymatic analysis indicates that DS application had a more substantial impact on soil metabolic activity than MF. Higher enzyme activities correlated with improved soil quality, suggesting that DS incorporation can be considered a valuable complement to MF in managing *C. avellana* varieties B and TDG.

4. Conclusions

This study represents an initial step toward utilizing thermally stabilized dry sludge (DS) as a sustainable alternative to mineral fertilization in *Corylus avellana*. DS application produced comparable effects to mineral fertilization on key physiological traits, while simultaneously enhancing soil quality and stimulating enzymatic activities such as acid phosphatase, β -glucosidase, and FDA hydrolysis. The lack of significant differences between DS and MF suggests that DS can be considered a viable nutritional alternative for hazelnut production, with the added advantages of reducing chemical fertilizer dependency, promoting microbial activity, and supporting long-term soil health.

These findings also emphasize the role of DS valorization as part of circular economy strategies linking aquaculture and agriculture. By integrating organic waste into productive systems, DS use contributes to resource efficiency and sustainability in fruit orchards. Nevertheless, further research under commercial orchard conditions and across different species and environments is required to validate these results, clarify the mechanisms involved, and assess potential long-term impacts.

Author Contributions: G.C. and E.J.-F. Conceptualization and methodology; S.C., A.P.-S.M. and V.H.-M. Field experiment; S.C., A.P.-S.M. and M.A. Laboratory methods. S.C. and A.P.-S.M. statistical analyses. S.C. and A.P.-S.M. Writing—original draft preparation. G.C., E.J.-F., V.H.-M., G.T., M.A., J.O. and S.O.O. revised and improved the current version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by VIPUCT 2020REGGC07 Project (G.C.).

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments: We thank Circular Solutions and Compañía Salmonífera Dalcachue. G.C. thanks the CYTED 121RT0110 Program.

Conflicts of Interest: The authors declare no conflicts of interest.

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