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Agronomic Performance and Nutrient Dynamics of Pelletized Organo-Mineral Fertilizers Derived from *H. illucens* and *T. molitor* Frass in Cabbage (*Brassica oleracea* L. var. capitata)

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Highlights

What are the main findings?

- Frass-based pellet fertilizers doubled cabbage yield and outperformed inorganic NPK at the same N dose.
- One formulation matched NPK yields with 40% less N, enhancing N and P use efficiencies.

What are the implications of the main findings?

- The precise application of these novel formulations significantly enhances overall soil health and agroecosystem performance, as validated by the ISCRI tool.
- Precise application of these formulations optimizes horticultural yield and agroecosystem health.

Abstract

The rapid growth of insect farming generates significant volumes of insect frass, a novel organic by-product. Utilizing frass-based organo-mineral fertilizers represents a sustainable alternative to synthetic fertilizers, yet long-term agronomic efficacy and residual effects require further field validation. This study evaluated pelletized organo-mineral formulations for conventional and organic agriculture, derived from *Hermetia illucens* and *Tenebrio molitor* frass. Eight field treatments were evaluated: an unfertilized control; an inorganic NPK fertilizer (150 kg N ha⁻¹); a biostabilized municipal solid waste compost at two nitrogen rates (150 and 300 kg N ha⁻¹); and two novel insect-frass-derived organo-mineral fertilizers (VHTI and VHTO) applied at a standard product dose (1000 kg ha⁻¹) and an N-equivalent dose (150 kg N ha⁻¹). Application of organo-mineral and organic treatments at the same nitrogen dose (150 kg N ha⁻¹) doubled cabbage yield compared to the unfertilized control and significantly outperformed the conventional inorganic treatment. These formulations demonstrated enhanced nitrogen and phosphorus use efficiencies, reflecting improved synchronization between nutrient release and crop demand. Furthermore, organo-mineral formulations significantly increased soil available phosphorus without adversely affecting key soil quality parameters. The Integrated Soil–Crop Response Index (ISCRI) confirmed a superior overall agroecosystem response for

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these treatments. These findings provide important theoretical insights into nutrient synchronization mechanisms in organo-mineral fertilizers, alongside practical applications for sustainable cabbage production. Consequently, frass-based pelletized fertilizers represent a highly sustainable, circular, and efficient alternative to optimize horticultural yield and nutrient use efficiency while enhancing soil health, ultimately supporting the valorization of insect farming by-products as viable substitutes for synthetic fertilizers.

Keywords: circular economy; insect frass; organo-mineral fertilizers; nutrient use efficiency; horticulture

1. Introduction

Global population growth has increased pressure on agricultural production and consumption systems, leading to a simultaneous rise in food demand and agro-industrial waste generation [1]. Consequently, modern agriculture faces significant challenges regarding environmental safety, waste management, and sustainable food availability [2]. Exceeding the planetary boundaries for reactive nitrogen (N) in the atmosphere and the progressive depletion of non-renewable nutrient sources, such as phosphorus (P), underscore the urgent need to identify sustainable fertilizer alternatives [3]. In this context, the recovery and recycling of nutrients from biodegradable organic waste have emerged as a key strategy to ensure the sustainability of agri-food systems within a circular economy framework [4,5].

The reuse of organic by-products through the development of organic and organo-mineral fertilizers reduces environmental impacts, maximizes resource efficiency, and improves soil health [6]. For instance, a substantial proportion of agricultural soils in southern Europe exhibit degraded surface layers, with organic carbon concentrations below 2% [7]. The application of organic amendments is essential to restore soil organic matter, improve physicochemical properties, and enhance overall plant performance [8]. To advance precision agriculture, recent research has focused on designing novel organo-mineral formulations by blending organic matrices (compost, vermicompost, manures, digestates, or biochar) with mineral fertilizers to optimize nutrient content and maximize crop yields [9].

A highly promising approach for the valorization of organic by-products is insect farming, specifically utilizing species like the black soldier fly (*Hermetia illucens*) or the yellow mealworm (*Tenebrio molitor*). These insects utilize organic substrates for sustenance, converting them into a nutrient-rich excreta mixture known as frass [10,11]. Insect frass possesses a high macro- and micronutrient content (NPK), substantial organic matter, a low microbial pathogen load, and potential biostimulant properties compared to traditional animal manures [12]. At the European level, this sector is growing rapidly, driven by favorable legislative frameworks such as the Fertilizing Products Regulation [13] which has explicitly recognized insect frass as a valid Component Material Category (CMC) for CE-marked fertilizers, opening the door to its commercial agronomic use. European production is currently estimated at 9500 tons per year and continues to scale [14]. However, despite the growing literature on traditional organic amendments the agronomic effects of insect frass remain inconclusive in many scenarios [15,16]. Frass composition varies widely depending on the rearing substrate, which directly influences crop yield and nutrient release dynamics [17–20].

Furthermore, technological advancements have optimized the physical delivery of these organic matrices. Pelletization and granulation offer a more efficacious format for

intensive farming, providing a higher concentration of nutrients per unit volume and reducing the time, dust and machinery fuel consumption associated with transport and field application compared to bulk organic amendments [21]. However, it must be noted that the manufacturing processes (drying, crushing and pelletization) entail their own energy costs, which should be carefully weighed against the high energy demands of synthetic fertilizer production (e.g., the Haber–Bosch process) on comprehensive life cycle assessments. Nevertheless, the field disaggregation of pellets is highly contingent on local meteorological conditions, irrigation management, and crop growth stages, which can sometimes delay the onset of their beneficial effects. Consequently, while pelletizing frass-based organo-mineral blends solves the physical handling issues, its impact on the synchronization between nutrient mineralization and crop uptake remains poorly understood.

Cabbage (*Brassica oleracea* var. capitata) is a globally pervasive crop cultivated across diverse climates due to its high adaptability. Because it is a high-yielding, intensive crop, cabbage is highly sensitive to nutritional deficiencies, making it an excellent model plant to evaluate the performance and nutrient release kinetics of novel fertilizer formulations [22]. Therefore, this study aimed to evaluate and compare the effectiveness of different formulations of pelletized organo-mineral fertilizers supplemented with insect frass in an open-field cabbage trial, with the ultimate purpose of proposing a sustainable alternative to chemical fertilizers and assessing their impacts on both plant performance and soil dynamics.

2. Materials and Methods

2.1. Study Area

The field experiment was carried out on a commercial farm located in the municipality of Picaña (Valencia, Spain) (39.43° N, 0.43° W; 35 m a.s.l.). The local climate is classified as Csa, corresponding to a typical Mediterranean climate according to the Köppen classification, characterized by hot, dry summers with mean temperatures above 22 °C and mild, wet winters. Annual rainfall in the area ranges from approximately 200 to 1000 mm. Meteorological data for the experimental period were obtained from a nearby weather station belonging to the Agroclimatic Information System for Irrigation (SIAR) network of the Spanish Ministry of Agriculture (Supplementary Materials, Figure S1).

The soil at the experimental site was classified as a Calcaric Fluvisol [23] and exhibited a clay loam texture with 32.1% sand, 20.7% silt, and 47.2% clay. In the topsoil layer (0–20 cm), pH (1:2.5 soil–water, *w/v*) and electrical conductivity (EC, 1:5 soil–water ratio) were 8.5 and 0.28 dS m^{−1}, respectively. The soil contained 1.10% soil organic carbon (SOC), 0.15% total nitrogen (TN), 143 mg kg^{−1} nitrate–nitrogen (N–NO₃[−]), with a cation exchange capacity (CEC) of 12.1 meq 100 g^{−1} and a bulk density of 1.6 Mg m^{−3}.

2.2. Experimental Design and Treatments

The experiment was conducted using a completely randomized design, with four replicates per treatment. Each experimental plot measured 1 m × 7 m (7 m²), with 1 m spacing between plots (Figure 1). Cabbage was cultivated under commercial field conditions as the test crop, with a planting density of 35 plants per plot (equivalent to 5 plants m^{−2}).

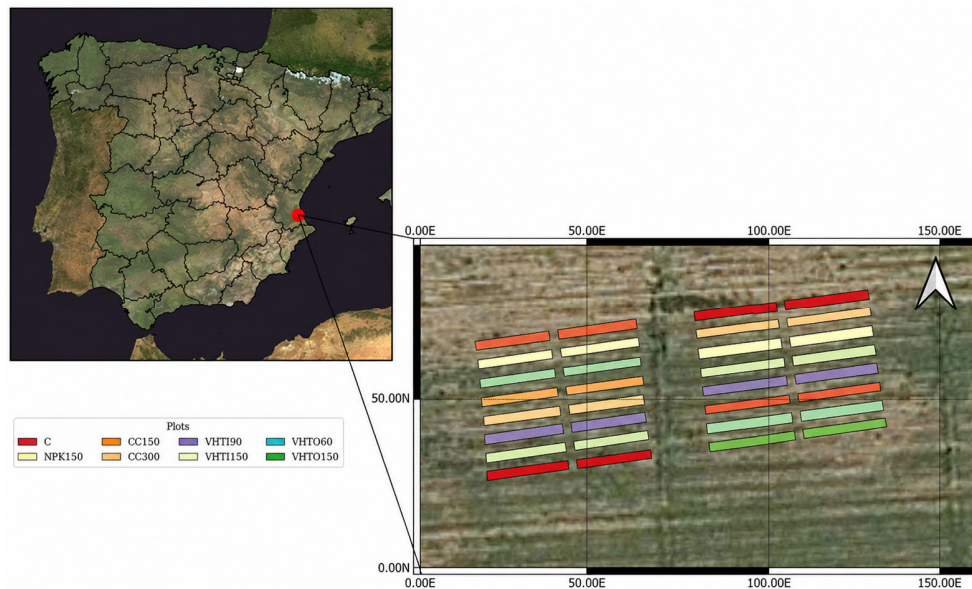


Figure 1. Location and experimental layout of the field trial in Picaña, Valencia (Spain). The map shows the geographical location within the Iberian Peninsula (**left**) and the spatial distribution of the eight fertilization treatments (**right**). Each colored rectangle represents an experimental plot. For treatment abbreviations and fertilizer composition, see Tables 1 and 2.

Eight fertilization treatments were evaluated: (i) unfertilized control (C); (ii) inorganic fertilizer (NPK 15-15-15, NPK); (iii) biostabilized organic amendment derived from the organic fraction of municipal solid waste (NPK 2-1-1, CC); (iv) organo-mineral fertilizer formulated for conventional agriculture (NPK 9-9-11, VHTI) and (v) organic fertilizer formulated for organic farming (NPK 6-8-6, VHTO). The treatments VHTI and VHTO were applied at two distinct rates: a standard product rate of 1000 kg ha⁻¹ (providing an identical product dose to NPK150) and a rate calculated to supply exactly 150 kg N ha⁻¹ (providing an identical product N dose to NPK150) (Table 1). The application rate of 150 kg N ha⁻¹ was selected based on the recommended N requirements for cabbage cultivation. This rate represents an optimal balance between meeting crop nutritional demands and minimizing the risk of N losses to the environment.

Table 1. Fertilizer composition and application rates for the experimental design conducted in Picaña, Valencia (Spain).

Treatments	NPK	Nitrogen Dose (kg N ha ⁻¹)	Fertilizer Rate (kg ha ⁻¹)
C	-	0	0
NPK150	15-15-15	150	1000
CC150	2-1-1	150	7500
CC300	2-1-1	300	15,000
VHTI90	9-9-11	90	1000
VHTI150	9-9-11	150	1666
VHTO60	6-8-6	60	1000
VHTO150	6-8-6	150	2500

C: control; NPK: inorganic fertilizer; CC: biostabilized; VHTI: organo-mineral fertilizer for conventional agriculture; VHTO: organo-fertilizer for organic farming.

2.3. Organo and Organo-Mineral Fertilizers: Composition and Characterization

The pelletized formulations were designed from an organic base blended with different organic and inorganic additives to obtain balanced nutrient compositions. The common organic base used in all formulations consisted of a mixture of vermicompost (25% fresh weight, f.w.) and insect frass derived from *H. illucens* (12.5% f.w.) and *T. molitor* (12.5% f.w.). The insect frass was obtained from Entogreen® (Santarem, Portugal). The vermicompost was produced at Compolab EPSO-UMH (Orihuela, Spain), using green waste and *Eisenia fetida* spp.

The organic fertilizer (VHTO) was supplemented (50% f.w.) with commercial blood meal (BLM) and commercial bone meal (BOM) as sources of N and P, respectively, and potassium sulfate (K_2SO_4), which is authorized for use in organic farming, as a source of K. In contrast, the organo-mineral fertilizer (VHTI) included inorganic additives such as urea (46-0-0), monoammonium phosphate (MAP, 12-61-0), and potassium nitrate (KNO_3) as N, P, and K sources, respectively. The biostabilized pellets (CC) were produced from the biostabilized organic amendment derived from the organic fraction of municipal solid waste. The raw compost was pelletized without the addition of any supplementary NPK-enriching additives or binders.

All pellets were developed and manufactured at CompoLab EPSO-UMH (Orihuela, Spain) by extrusion using a small-scale pelleting machine (4 kW, 60–70 kg h^{−1} capacity), producing pellets with an average length and a diameter of 6 mm. The physicochemical characteristics of the raw materials and the final fertilizers are presented in Table 2.

The physicochemical and chemical properties of the fertilizers (Table 2) were determined according to [24]. In summary, the pH and EC of the water-soluble extracts (1:10 w/v) were analyzed. The determination of total organic carbon (TOC) and TN was conducted using an automatic elemental microanalyzer, while the quantification of total organic matter (OM) was performed by loss on ignition at 430 °C for 24 h. The moisture content was determined by oven drying at 105 °C for 24 h. The concentrations of macronutrients (P, K, Ca, Mg) were quantified using ICP-OES following microwave-assisted acid digestion in a nitric acid/water mixture (1:1 v/v). The organic and organo-mineral formulations were specifically designed to contain a minimum of 50% OM, and all heavy metal concentrations complied with the limits established by Spanish legislation for fertilizer products [25].

Table 2. Physicochemical characteristics of raw materials used for organo-mineral biofertilizer formulation and the characterization of organic and organo-mineral fertilizers (Data expressed on dry basis).

Acronym	pH	EC (dS m ^{−1})	OM (g kg ^{−1})	TOC (g kg ^{−1})	TN (g kg ^{−1})	P (g kg ^{−1})	K (g kg ^{−1})	Ca (g kg ^{−1})
Raw materials								
V	7.8	2.40	264	204	14.8	13.5	6.8	130
FHI	7.9	9.43	855	456	32.0	30.6	38.6	3.03
FTM	5.9	5.10	877	431	37.2	33.5	19.6	5.56
BLM	7.2	1.56	974	565	150	8.9	3.5	0.40
BOM	7.1	0.49	263	151	31.9	48.2	0.6	23.2
Organic and organo-mineral fertilizer								
CC	7.0	6.90	599	339	17.5	9.1	9.6	40.8
VHTI	5.7	42.3	560	205	87.8	86.0	110	13.3
VHTO	6.7	14.3	551	309	59.4	84.8	58.3	88.7

FHI: Frass *H. illucens*, FTM: Frass *T. molitor*, V: vermicompost, BLM: commercial blood meal, BOM: commercial bone meal, EC: electrical conductivity, OM: organic matter, TOC: total organic carbon, TN: total nitrogen. For abbreviations, see Table 1.

2.4. Crop Management and Treatment Application

The trial was conducted under a conventional tillage system. The preceding crop was potato (*Solanum tuberosum*), and the soil was prepared by ridging prior to transplanting. The experiment involved the transplantation of cabbage (*Brassica oleracea* var. capitata) seedlings on 26 March 2023, which were subsequently harvested on 16 June 2023. The crop was irrigated using a surface gravity system (flooding), which was applied on three occasions. The irrigation water exhibited the following primary characteristics: pH 8.64, EC 2.96 dS m⁻¹, sodium (Na⁺) 243 mg L⁻¹, and chloride (Cl⁻) 408 mg L⁻¹. The water quality analysis revealed an adequate Ca:Mg ratio but indicated a moderate to high salinization risk.

Conventional agricultural practices were employed, implementing pest and disease control measures using authorized products at recommended doses. The experimental plots were managed under uniform agronomic conditions throughout the trial. Fertilizer treatments were applied and incorporated into the soil (0–10 cm depth) using hand rakes prior to transplantation.

2.5. Soil and Plant Sampling and Analysis

The effects of the different fertilization treatments on the physicochemical properties of the soil were evaluated based on topsoil samples (0–20 cm depth), obtained using a stainless-steel probe. Samples were collected at various points within the plots (5 sub-samples) and subsequently homogenized to obtain four composite soil samples per treatment. To ascertain the residual effects of fertilization on the soil, samples were taken at the time of sowing (Ti: 0 days) and at harvest (Tf: 80 days). The samples were air-dried and sieved at 2 mm. All analyses were carried out in triplicate. The Ti sampling was performed immediately after the application and thorough mixing of the treatments into the soil. pH was measured in a 1:2.5 soil:water (*w/v*) extract and EC in 1:5 (*w/v*). The determination of organic matter (OM), total Kjeldahl nitrogen (TN), and available P (P_{ext}) followed the methods of [26]. The inorganic forms of nitrogen (NO₃⁻-N and NH₄⁺-N) were measured in a 1:5 (*w/v*) extract with 0.2 M KCl (K-365, BÜCHI Labortechnik AG, Flawil, Switzerland) [27].

At physiological maturity, five cabbage heads were hand-harvested per treatment plot. The following parameters were recorded for each treatment: yield, average head weight and head dimensions (height and diameter). After harvest, the samples were oven-dried at 60 °C for 48 h and then weighed to determine dry biomass. Total nitrogen (TN) in plant tissues was determined using an automatic elemental microanalyzer (EuroVector Elemental Analyzer, Milan, Italy). Following HNO₃/HClO₄ digestion, phosphorus (P), micronutrients, and potentially toxic elements were quantified by ICP-OES (ICAP 6500 DUO, Agilent Technologies, Santa Clara, CA, USA).

Nitrogen use efficiency (NUE; expressed as the percentage of the applied N-fertilizer taken up in the cabbage) was calculated using the N difference method, with the total N of the unfertilized treatment as the control [28]. Phosphorus and potassium use efficiency (PUE and KUE, respectively) were calculated in the same way.

2.6. Integrated Soil–Crop Response Index (ISCRI)

While individual soil and crop variables provide specific insights, analyzing them in isolation may occasionally reveal contradictory trends, making it difficult to evaluate the overall sustainability of a treatment. To synthesize the direction and intensity of fertilizer-induced changes in crop and soil relative to the control treatment more effectively, we applied the Integrated Soil–Crop Response Index (ISCRI) following the modified integrated response approach described by [29]. Unlike individual metrics, the ISCRI provides a holistic evaluation of the agroecosystem by quantifying the distance between

different measured parameters in the cabbage and soil under each treatment, whether this distance is positive or negative in relation to the reference condition (the unfertilized control). The ISCRI was calculated as follows:

(i) Calculate the mean value for each parameter per treatment. For each measured parameter j (cabbage yield, soil OM, soil macronutrients and plant nutrient uptake) and each fertilizer treatment k , calculate the arithmetic mean across all replicates ($n = 4$):

$$\bar{X}_{j,k} = \frac{1}{n} \sum_{i=1}^n X_{j,i,k} \quad (1)$$

where:

$X_{j,i,k}$ = the measured value of parameter j for replicate i under treatment k .

(ii) Transform the mean into a log-ratio relative to the control. For each parameter j and treatment kk , calculate $Y_{j,k}$, which represents the proportional change (positive or negative) relative to the reference condition (the control treatment, $X0_j$):

$$Y_{j,k} = \log\left(\frac{\bar{X}_{j,k}}{X0_j}\right) \quad (2)$$

If $\bar{X}_{j,k} > X0_j$, $Y_{j,k}$ is positive. If $\bar{X}_{j,k} < X0_j$, $Y_{j,k}$ is negative. The log transformation standardizes the scale of responses across different parameters.

(iii) Standardize the deviation. To make parameters with different units and variances comparable, each log-response is divided by the standard deviation of all Y values for that parameter across all treatments:

$$A_{j,k} = \frac{Y_{j,k}}{\sigma_{Y_j}} \quad (3)$$

where:

σ_{Y_j} = the standard deviation of $Y_{j,k}$ for parameter j across all k treatments.

$A_{j,k}$ is now a unitless, standardized score that indicates how many “standard deviation units” treatment k deviates from the control for parameter j .

(iv) Sum all standardized deviations to obtain the final ISCRI score. For each treatment kk , sum the standardized scores $A_{j,k}$ across all J measured parameters (both crop and soil):

$$\text{ISCRI value} = \sum_{j=1}^J A_{j,k} \quad (4)$$

2.7. Statistical Analysis

Statistical analyses were performed using the InfoStat package v4.3.1 [30] and R software v4.3.0 [31]. Prior to the analysis, data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene tests, respectively. A one-way analysis of variance (ANOVA) was used to evaluate differences among the fertilization treatments. When significant differences were detected ($p < 0.05$), Fisher’s least significant difference (LSD) test ($\alpha = 0.05$) was applied for multiple comparisons. Results are presented as mean values $\pm$ standard error (SE) ($n = 4$).

3. Results

3.1. Evolution of Soil Parameters

Significant differences were detected in several soil physicochemical parameters following the application of the organic and organo-mineral fertilizers (Figure 2). At the beginning of the experiment (Ti), a significant reduction in soil pH was observed in the treatments applied at the highest doses, particularly in VHT150, which exhibited the lowest value (7.72). By the end of the trial (Tf), soil pH increased across all treatments;

however, significant differences persisted, with CC300 showing the highest value (8.54) and VHTI90 the lowest (8.13).

Regarding EC, no statistically significant variation was observed among treatments at Ti. At Tf, significant differences emerged, with the unfertilized (C) treatment exhibiting the highest EC value (0.77 dS m^{-1}), while NPK150 and CC300 showed the lowest values (0.61 and 0.58 dS m^{-1} , respectively). The initial OM content was significantly higher in CC150, CC300, and VHTI150, although no differences among treatments were detected at Tf.

With regard to available phosphorus (P_{ext}), the highest concentrations at Ti were observed in both VHTI doses, whereas CC300 and VHTO150 exhibited values statistically similar to the unfertilized control (Figure 2D). Greater variation among treatments was observed at Tf, with VHTI150 demonstrating the absolute highest available P level, followed by VHTI90 and NPK150.

Initial TN differed significantly among treatments, with VHTI150 and VHTO150 presenting the highest contents (Figure 2E). At Tf sampling, these initial disparities were no longer evident, showing no statistically significant differences among any of the treatments (Figure 2E). Initial nitrate ($\text{NO}_3\text{-N}$) concentrations were comparable to the control, with the exception of both VHTI doses, which showed outstandingly higher values (Figure 2F). At Tf sampling, minor discrepancies were identified, primarily driven by slight increases in the control and VHTO60 treatments (Figure 2F).

Overall, the dynamics of both available and non-available macronutrient forms in the soil were strongly influenced by the nature of the fertilizer applied (organic, mineral or organo-mineral). The organo-mineral and mineral formulations generally promoted a more rapid alteration of the soil physicochemical and nutritional status compared to the strictly organic amendments.

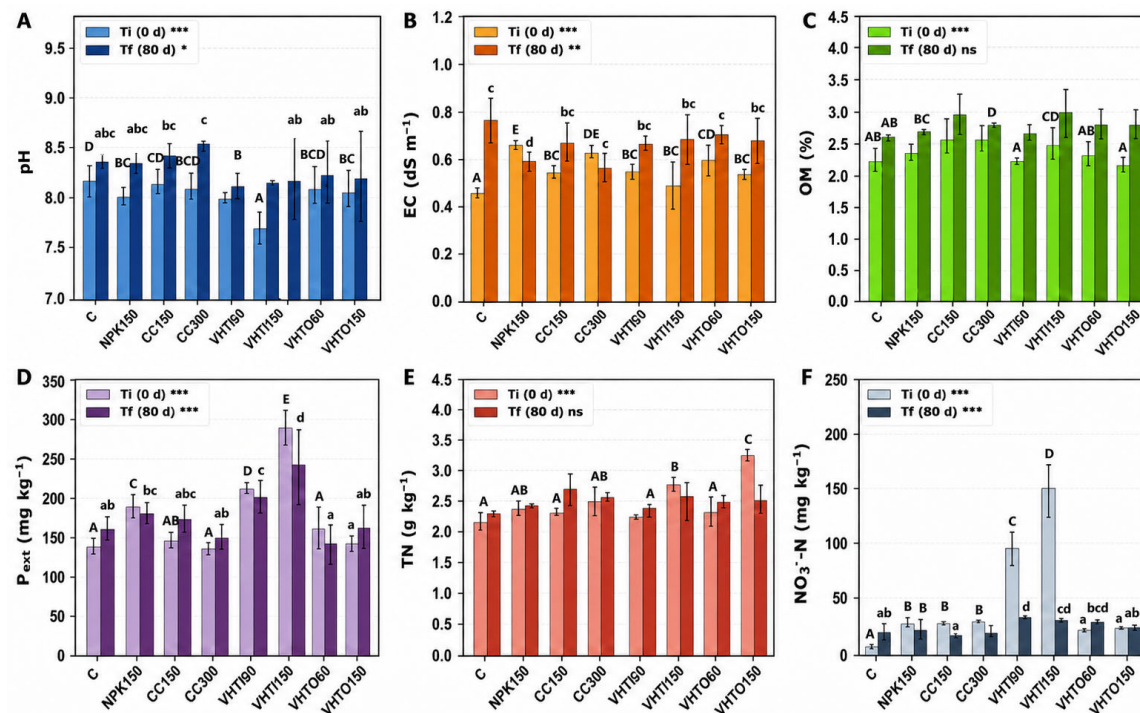


Figure 2. Physicochemical properties of the soil under different fertilization treatments at the initial (Ti) and final (Tf) experimental times. (A): pH, (B): electrical conductivity, (C): organic matter, (D): available phosphorus, (E): total nitrogen, (F): nitrate. For each variable, different capital letters

within a column indicate significant differences among treatments at Ti (0 days), while different lowercase letters indicate significant differences at Tf (80 days), between treatments ($p < 0.05$). *, **, ***: significant difference between treatments at $p < 0.01$, $p < 0.001$ and $p < 0.0001$, respectively. n.s.: not significant. Bars indicate mean $\pm$ SE ($n = 4$). For acronyms, see Table 1.

3.2. Agronomic Performance and Yield Components

Cabbage yield was significantly affected by the fertilization treatments ($p < 0.001$). All fertilized treatments, with the exception of CC300, produced significantly higher yields than the unfertilized control. When comparing fertilizers at the same N dose (150 kg N ha⁻¹) yield increased in the order NPK150 $\leq$ CC150 $<$ VHTO150 $\leq$ VHTI150 (Table 3). Yield increases relative to the control were 100% for VHTI150 and VHTO150 treatments. When comparing fertilizers at the same product dose (1000 kg ha⁻¹), NPK150 (46,270 kg ha⁻¹) and VHTI90 (43,556 kg ha⁻¹, providing 90 kg N ha⁻¹) showed similar yields, while VHTO60 (35,171 kg ha⁻¹, providing 60 kg N ha⁻¹) exhibited a lower yield. Regarding the effect of doubling the biostabilized compost dose, CC300 (300 kg N ha⁻¹) showed a yield (33,013 kg ha⁻¹) significantly lower than CC150 (49,556 kg ha⁻¹) and statistically similar to the unfertilized control.

Head diameter was significantly influenced by the treatments ($p < 0.001$), with VHTO150 and VHTI150 exhibiting the greatest values (20.8 cm and 19.6 cm, respectively), significantly exceeding those observed in the control and CC300. In contrast, head height was not significantly affected by the fertilization strategies. Overall, the high-dose organo-mineral and organic fertilizers (VHTI150, VHTO150) maximized both yield and head diameter, while the conventional and biostabilized treatments (NPK150, CC150) performed comparably to the lower-dose organic and organo-mineral variants (VHTI90, VHTO60).

Table 3. Yield and characterization of cabbage under commercial field conditions.

Treatments	Head Height (cm)	Head Diameter (cm)	Yield (kg ha ⁻¹)
C	10.1 $\pm$ 1.0	16.2 $\pm$ 1.2 ab	28,089 $\pm$ 4553 a
NPK150	10.8 $\pm$ 0.5	17.7 $\pm$ 1.9 bcd	46,270 $\pm$ 8458 c
CC150	11.6 $\pm$ 1.1	18.9 $\pm$ 1.7 cde	49,556 $\pm$ 8534 cd
CC300	11.3 $\pm$ 4.5	15.4 $\pm$ 2.0 a	33,013 $\pm$ 6665 a
VHTI90	11.1 $\pm$ 0.8	17.7 $\pm$ 1.4 bcd	43,556 $\pm$ 7652 bc
VHTI150	12.1 $\pm$ 1.3	19.6 $\pm$ 1.4 de	57,808 $\pm$ 10,432 d
VHTO60	11.2 $\pm$ 0.6	16.8 $\pm$ 0.9 abc	35,171 $\pm$ 5052 ab
VHTO150	12.1 $\pm$ 0.8	20.8 $\pm$ 3.7 e	56,445 $\pm$ 6673 d
F-value	n.s.	5.24 ***	11.95 ***

Significant levels: *** $p < 0.0001$; n.s.: not significant. Different letters within a column indicate significant differences between treatments ($p < 0.05$). Values indicate mean $\pm$ SE ($n = 4$). For acronyms, see Table 1.

The macro- and micronutrient contents measured in the cabbage tissues were within the adequate nutritional ranges reported under commercial production conditions (Supplementary Materials, Table S1). TN content increased significantly with fertilizer application, particularly under VHTO150, VHTO60, and VHTI150, which recorded the highest values. While P and K contents did not show significant differences among treatments, K levels tended to be numerically higher in CC150. Regarding micronutrients, Ca and Na concentrations were significantly affected by the treatments, whereas Fe, Mn, Zn, and Cu did not differ significantly.

Beyond absolute nutrient uptake, the efficiency of nutrient utilization was evaluated to determine the physiological performance of each fertilization strategy (Figure 3A–C). NUE showed significant differences among treatments ($p < 0.001$) (Figure 3D). At the same nitrogen dose (150 kg N ha^{-1}), the organic (VHTO150) and organo-mineral (VHTI150) fertilizers exhibited substantially higher NUE than the conventional inorganic fertilizer (NPK150) and the biostabilized compost (CC150). This indicates that organic and organo-mineral formulations enhance N conversion into biomass more effectively than conventional inorganic fertilization. At the same product dose (1000 kg ha^{-1}), VHTI90 (90 kg N ha^{-1}) achieved a NUE of 31%, comparable to NPK150 (24%) despite the lower N input, further confirming the superior efficiency of the organo-mineral formulation. In contrast, doubling the biostabilized compost dose (CC300) resulted in the lowest NUE (4%), indicating a negative dose–response effect for this material.

PUE also showed statistically significant differences among treatments ($p < 0.001$) (Figure 3E). The biostabilized compost at 150 kg N ha^{-1} (CC150) exhibited the highest PUE (12%), significantly exceeding all other treatments. The organic and organo-mineral fertilizers at a high dose (VHTI150 and VHTO150) showed intermediate PUE values (6–7%), while the lowest values were recorded for CC300 (4%) and VHTO60 (4%). This suggests that the biostabilized compost, despite its lower yield performance compared to VHTI150 and VHTO150, is particularly efficient at enhancing phosphorus utilization.

KUE was significantly influenced by fertilization ($p < 0.001$) (Figure 3F). CC150 exhibited the highest KUE (73%), followed by VHTO150 (47%) and VHTI150 (42%). In contrast, CC300 showed the lowest KUE (5%), comparable to the unfertilized control. The superior KUE of CC150, combined with its high PUE, indicates that biostabilized compost is particularly effective at enhancing the utilization of P and K, even though its overall yield performance is limited by N constraints.

Overall, the organo-mineral and organic formulations applied at the optimal dose of 150 kg N ha^{-1} consistently demonstrated superior nitrogen use efficiency and yield performance compared to the conventional inorganic fertilizer.

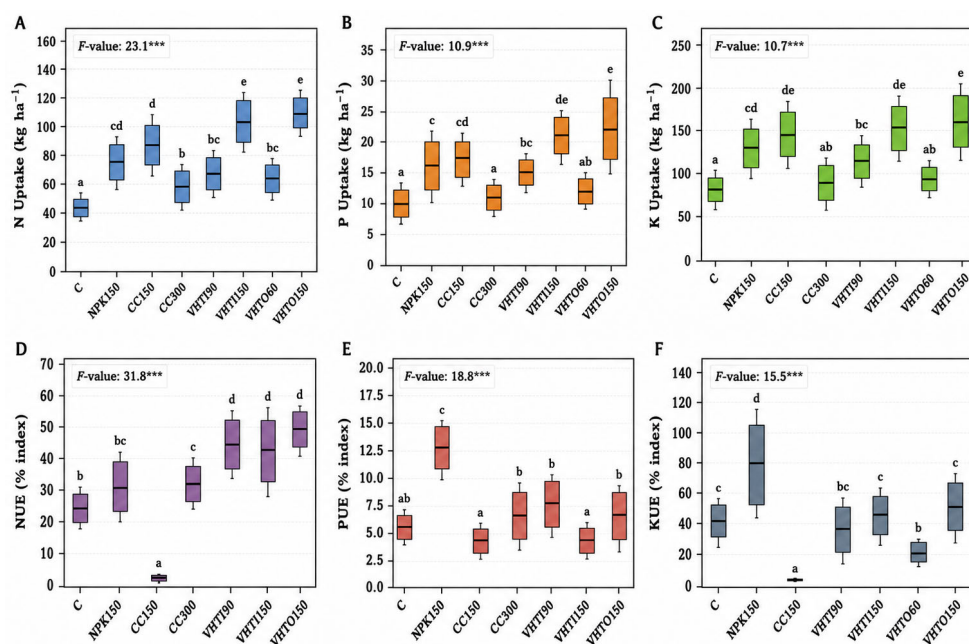


Figure 3. Nutrient uptake (N, P, K: (A–C)) and use efficiency indices (NUE, PUE, KUE: (D–F)) of cabbage under different fertilization treatments. Different letters within a column indicate

significant differences between treatments ($p < 0.05$). ***: significant difference between treatments at $p < 0.0001$. Boxes indicate mean $\pm$ SE ($n = 4$). For acronyms, see Table 1.

3.3. Implications of the Integrated Soil–Crop Response Index (ISCRI)

The values ranged from -1.37 to $+7.42$ in the following order: $VHTI150 > VHTO150 > CC150 > VHTI90 > NPK150 > VHTO60 > CC300$ (Figure 4A). The highest cumulative scores were obtained for the high-dose organo-mineral, organic and biostabilized treatments, indicating the most favourable overall effect on the agroecosystem. The starplots show these high scores reflect a consistent positive response across both crop variables (yield, NPK uptake) and soil parameters (TN and OM) with the colored polygons extending well beyond the reference baseline (dotted line) of the control treatment (Figure 4B–H).

On the other hand, doubling the biostabilized compost dose (CC300) resulted in the only negative ISCRI value (-1.37). The starplot for this treatment (Figure 4D) shows that the response polygon is largely contained within the reference baseline, indicating a detrimental effect on key variables such as yield, N uptake and soil Pext. The NPK150 demonstrated a positive ISCRI value ($+2.73$), reflecting a favorable response, nevertheless less pronounced than the high-dose organic and organo-mineral treatments (Figure 4B). VHTI90 achieved a higher ISCRI ($+3.48$) than NPK150 despite supplying 40% less nitrogen, further highlighting its superior efficiency (Figure 4F). Finally, VHTO60 showed a low score ($+0.12$) limited by its minimal impact on both crop uptake and soil parameters (Figure 4G).

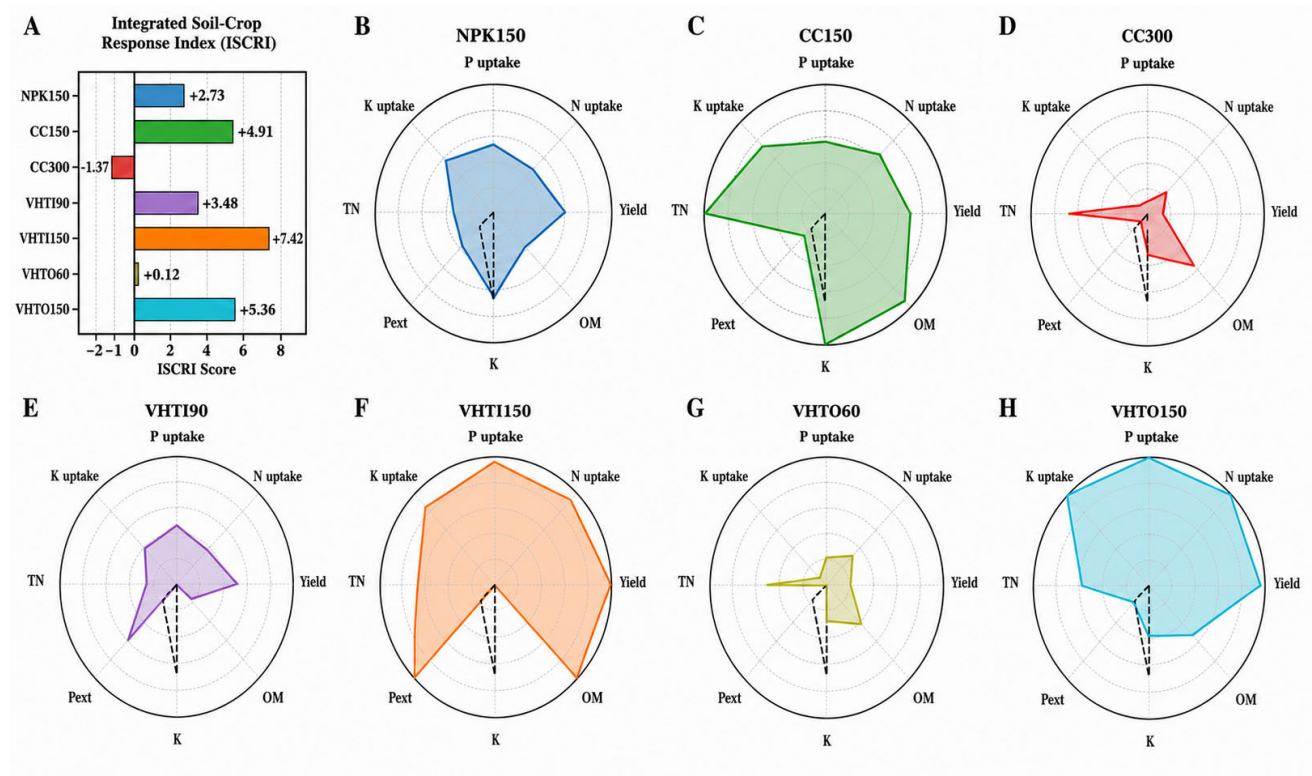


Figure 4. (A): ISCRI evaluation of the fertilization treatments. (B–H): radar charts illustrating the individual contributions of the evaluated agronomic and soil variables (yield, N uptake, P uptake, K uptake, TN, OM and Pext) to the ISCRI for each specific treatment. The black dotted polygon represents the baseline reference condition (unfertilized control). For acronyms, see Table 1.

4. Discussion

4.1. Effects of Organo-Mineral Fertilization on Soil Properties

The application of organo-mineral and organic treatments induced immediate alterations in soil physicochemical properties, particularly evident by the significant differences observed at Ti immediately after treatment incorporation. VHTI150 showed the most pronounced effects, with significantly lower pH compared to the control. This acidification is attributed to the dose-dependent release of ammonium from the frass component and its subsequent nitrification, as well as the presence of organic acids in the formulation [15]. The high nitrate levels in VHT150 at Ti confirm rapid mineralization of the organic substrate. However, at Tf, pH values converged across all treatments demonstrating the buffering capacity of the calcareous soil [32]. EC showed an inverse pattern between the control and fertilized treatments over time. At Ti, amended soils had slightly higher EC due to soluble salts in the fertilizers. On the other hand, at Tf the control exhibited the highest EC, while all fertilized treatments showed lower values. This is explained by the highest cabbage growth in fertilized plots, which resulted in substantial nutrient uptake (removing soluble ions from the soil solution) and increased soil cover (reducing direct evaporation and salt concentration). In contrast, limited plant growth in the control led to nutrient accumulation and salt concentration through direct evaporation [33]. OM increased significantly at Ti only in treatments with bioestabilized treatments, consistent with their high inherent OM content. Despite the absence of statistically significant differences, all treatments maintained higher OM values compared to the control. This suggests that, while the labile carbon fraction was mineralized (supporting nutrient release as evidence by higher nitrate at Ti), the recalcitrant humic fraction persisted in the soil. Additionally, enhanced root biomass from the cabbage plants in fertilized treatments contributed to maintaining soil OM levels [34].

The elevated initial nitrate levels observed in the VTI treatments were directly attributable to the use of KNO_3 as the N source in their formulation, which provides immediately available nitrate. Conversely, the conventional mineral fertilizer treatment relied on urea. In calcareous soils with high pH, urea is highly susceptible to hydrolysis and subsequent ammonia volatilization [35]. This volatilization loss likely contributed to the lower NUE observed in the conventional treatment compared to the organo-mineral formulations, which protected a portion of the N within the organic matrix.

Pext proved highly sensitive to the type of fertilizer applied. At Ti sampling, the highest values were recorded in the VHTI90 and VHTI150 treatments, by the rapid dissolution of the inorganic fraction coupled with the mineralization of the frass [36]. These differences widened at Tf of the experiment, suggesting a more sustained release dynamic in the organo-mineral treatments, whereas the strictly organic treatments remained closer to the control values. Furthermore, applying fertilizers based on crop N requirements can lead to the over-application of other nutrients. The VHTI90 and VTI150 treatments resulted in a substantial increase in soil available P. While beneficial for the current crop, continuous application of such P-rich formulations over successive cropping cycles could lead to excessive P accumulation in the soil, posing potential environmental risks [37].

Initial TN values were significantly higher in the high-dose organo-mineral and organic treatments (VHTI150 and VHTO150). However, at Tf these treatments exhibited some of the lowest TN values, suggesting high mobilization and uptake by the crop, or greater transformation into inorganic forms with subsequent loss via leaching or volatilization [18]. Initial N-NO_3^- concentrations were substantially higher than the control in both VHTI doses, while at Tf, the variability among treatments decreased as the available N was consumed by the crop [38].

4.2. Effects of Organo-Mineral Fertilization on Agronomic Performance

The experimental design allowed for two critical agronomic comparisons: (i) treatments delivering the same N dose (150 kg N ha⁻¹) and (ii) treatments applied at the same fertilizer rate (1000 kg ha⁻¹). When fertilizers were compared at the same N dose, VHTO150 and VHTI150 pelletized fertilizers significantly outperformed both the NPK150 and CC150 treatments. This finding is particularly relevant because it demonstrates that organic and organo-mineral pellet formulations can achieve higher yields without increasing nitrogen inputs. The yield enhancement observed in the present study is attributed to the substantial initial supply of N and P provided by the organo-mineral and organic treatments. These nutrients supported vigorous cabbage growth throughout the crop cycle [39]. Cabbage head diameter followed the same pattern, confirming that the biomass gains were structurally reflected in marketable yield.

When comparing fertilizers at the same fertilizer dose (1000 kg ha⁻¹), the organo-mineral fertilizer VHT90 (90 kg N ha⁻¹) achieved a yield comparable to NPK150 (150 kg N ha⁻¹), representing a 40% reduction in N input without yield penalty. This suggests that the organo-mineral pellets have a higher NUE. In contrast, the organic fertilizer VHTO60 (60 kg N ha⁻¹) showed lower yield, indicating that the organo-mineral matrix is more effective at low application rates. These findings align with previous studies reporting that organo-mineral fertilizers combine the benefits of organic matter and mineral nutrients, resulting in improved nutrient availability and crop performance [40].

4.3. Nutrient Use Efficiency and Agroecosystem Assessment via ISCRI

The efficiency of nutrient utilization highlighted distinct physiological responses tied to the experimental design. NUE showed a clear advantage for the iso-N dose treatments: significantly higher for VHTO150 (46%) and VHTI150 (42%) than NPK150 (24%) and CC150 (30%). This indicates that organic and organo-mineral pellets enhance N conversion into biomass more effectively than conventional inorganic fertilization, likely due to reduced leaching losses and better rhizosphere synchronization [41]. At the same fertilizer dose, VHTI90 achieved a NUE of 31%, comparable to NPK150 despite the lower N input, confirming the efficiency of the organo-mineral formulation.

PUE showed a difference between treatments, the CC150 exhibited the highest PUE (12%). This suggests that the biostabilized compost, despite its lower yield performance compared to VHTI150 and VHTO150, is particularly efficient at enhancing P utilization, possibly through microbial solubilization or improved cation exchange capacity in the calcareous soil matrix [42]. KUE was highest in CC150 (73%), followed by VHTO150 (47%) and VHTI150 (42%). The superior PUE and KUE of CC150 indicate that biostabilized compost is particularly effective at enhancing the utilization of secondary macronutrients, even though its overall yield performance is limited by N constraints. The lack of significant statistical variation in K dynamics across most treatments suggests that K mobility in this soil–plant system is highly buffered, diminishing the capacity of efficiency indices to discern treatment-induced variations under these specific conditions [43].

However, doubling the biostabilized compost dose (CC300) resulted in the lowest efficiencies across all indices (NUE: 4%; PUE: 4%; KUE: 5%). This suggests that excessive application of biostabilized amendment can engender negative effects on crop performance, potentially driven by microbial N immobilization, osmotic stress or phytotoxicity from accumulated organic acids [44,45]. This dose-dependent response confirms that simply increasing the total nutrient supply does not necessarily translate to improved agronomic efficiency, highlighting the critical importance of precise formulation and appropriate application rates for these types of organic materials.

The ISCRI provided an integrated validation of the treatment effects, following the order: VHTI150 > VHTO150 > CC150 > VHTI90 > NPK150 > VHTO60 > CC300. The highest

cumulative scores were obtained for the high-dose organo-mineral, organic, and biostabilized treatments, reflecting the most favorable overall effect on the agroecosystem. The starplots illustrate that these high scores correspond to a consistent positive response across both crop variables (yield, NPK uptake) and soil parameters (TN and OM), with response polygons higher than the reference baseline. VHTI90 achieved a higher ISCRI (+3.48) than NPK150 (+2.73) despite supplying 40% less N, reinforcing the efficiency advantage observed in yield and NUE data. On the other hand, CC300 was the only treatment yielding a negative ISCRI (−1.37), with its response polygon largely contained within the control treatment baseline, confirming the negative effect of excessive bioestabilized compost application. These findings corroborate that pelletized organo-mineral and optimized organic formulations facilitate a more balanced nutritional impact on both soil health and crop status without adverse effects, consistent with responses reported in other cropping systems [22,46].

5. Conclusions

This study demonstrates that pelletized organo-mineral and organic fertilizers incorporating *H. illucens* and *T. molitor* frass are effective alternatives to conventional fertilization in cabbage crops. At the same N dose (150 kg N ha^{−1}), both VHTI150 and VHTO150 doubled cabbage yield compared to the control, while the organo-mineral formulation VHTI90 achieved comparable yields to NPK150 with 40% less N input. These formulations enhanced nutrient use efficiency and soil properties through synchronized nutrient release aligned with crop demand. In contrast, the high dose of biostabilized amendment (CC300) resulted in lower yields and the lowest nutrient use efficiencies, likely due to excessive application of partially stabilized organic material causing nitrogen immobilization or phytotoxic effects. This highlights the importance of appropriate application rates for biostabilized amendments.

The ISCRI confirmed the benefits of frass-based fertilizers on the agroecosystem, with VHTI150 and VHTO150 achieving the highest positive responses. Frass-based pelletized fertilizers represent a sustainable, circular alternative for horticultural production that valorize insect farming by-products. Future research should evaluate their long-term effects on soil microbiology dynamics and performance across diverse cropping systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12080912/s1>, Figure S1. Climate data for Picaña (Valencia, Spain) during the 2023 experimental period. Table S1. Macro- and micronutrient content concentrations in cabbage tissues under different fertilization treatments.

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