AgriEngineering

MDPI

Article

Evaluation of the Incidence of Mineral Fertilizer Entrapment in Organic Matrix of Residual Biosolids, Cellulose and Sawdust in Maize (*Zea mays*) Crop

Rodrigo Ramírez Palacios [1,*], Wanderley José Melo [2], Antonio Mauricio Souza Rocha [2], Ademir Sérgio Ferreira Araújo [3], Nora Restrepo-Sánchez [1,*] and Carlos Alberto Peláez Jaramillo [1]

[1] Molecular Studies Interdisciplinary Research Group, Faculty of Exact and Natural Sciences, University of Antioquia—UdeA, Calle 70 No. 52-21, Medellín 050021, Colombia
[2] Department of Agricultural and Environmental Biotechnology, Faculty of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal Campus, São Paulo 01049-010, SP, Brazil
[3] Soil Quality Laboratory, Agricultural Science Center, Fundação Universidade Federal do Piauí, Teresina 64049-550, PI, Brazil
* Correspondence: rodrigo.ramirezp@udea.edu.co (R.R.P.); neugenia.restrepo@udea.edu.co (N.R.-S.)

Abstract

Sustainable fertilizers are needed to improve nutrient efficiency and reduce environmental impacts. Greenhouse experiments were conducted to evaluate matrix-based organo-mineral fertilizers (OMFs) for *Zea mays* over 60 days. The study took place during the dry season in Jaboticabal, São Paulo, using 5.5 dm^3 plastic pots. Biosolids, deinked paper sludge (cellulose), and sawdust were used as organic matrices. Four treatments (n = 6) were tested: BC (biosolids/cellulose), BS (biosolids/sawdust), FF (uncoated NPK), and NF (no fertilizer). FF received 4.0 g NPK (4-14-8) per pot in two split doses; BC and BS each received 2.0 g NPK entrapped in 2.0 g matrix, applied once at sowing. BC provided the most controlled nutrient release and outperformed FF, increasing plant height by 20.4%, stem diameter by 13.7%, and leaf area by 5.3%. Considering nutrient uptake, BC exceeded FF by 22.5% for N, 38.6% for P, and 22.7% for K while using half the mineral fertilizer. Overall, matrix-based OMFs improved *Zea mays* growth and nutrient assimilation and may reduce nutrient losses relative to conventional split applications. Because the results derive from a single dry-season greenhouse trial with pots, field-scale validation to the production stage is required to confirm agronomic performance and quantify economic and environmental benefits.

Keywords: slow-release fertilizer; nutrient assimilation; plant biomass; organic matrix; biosolid; cellulose

check for updates

Academic Editor: Francesco Marinello

Received: 21 July 2025
Revised: 14 September 2025
Accepted: 17 September 2025
Published: 11 October 2025

Citation: Palacios, R.R.; Melo, W.J.; Rocha, A.M.S.; Araújo, A.S.F.; Restrepo-Sánchez, N.; Jaramillo, C.A.P. Evaluation of the Incidence of Mineral Fertilizer Entrapment in Organic Matrix of Residual Biosolids, Cellulose and Sawdust in Maize (*Zea mays*) Crop. *AgriEngineering* **2025**, 7, 343. https://doi.org/10.3390/agriengineering7100343

1. Introduction

The agricultural sector has employed large amounts of synthetic fertilizers to satisfy the high demand for food, with consumption increasing dramatically throughout the 21st century [1]. A significant increase is expected worldwide at a rate of 2.5 million metric tons per year [2]. These fertilizers, commonly known as synthetic or inorganic fertilizers (IFs), usually contain at least one of these three nutrients: nitrogen (N), phosphorus (P), or potassium (K). IFs increase soil acidity, and because they do not provide organic matter, they reduce microbial activity in agroecosystems [3–5]. In addition, IFs can be easily hydrolyzed and, when applied, tend to be lost through runoff, leaching, and volatilization.

Depending on the application methodology and climatic conditions, losses of up to 90% have been reported [6]. The uncontrolled release of nutrients generates economic losses for the agricultural sector and represents environmental risks, such as the contamination of aquifers by nitrate leaching. Increased nitrogen levels can be unhealthy for livestock, fish, and humans, particularly infants. The volatilization of nitrogen gases like ammonia and nitrous oxide is also known to increase greenhouse gas emissions [7,8]. This phenomenon occurs with inorganic fertilizers because they do not have properties that protect them from rapid degradation in the soil.

To mitigate these harmful effects, mechanisms such as encapsulating fertilizers with coatings or interactive materials have been developed to allow a slower release of nutrients [9,10]. These formulated materials are called slow-release fertilizers (SRFs), which increase water retention capacity and reduce nutrient losses by lowering the amount of fertilizer needed to ensure maximum crop yields. Coated fertilizers are the main category, prepared by coating synthetic fertilizer granules with a semi-permeable layer [11–14]. SRFs involve the use of superabsorbents as hydrophilic polymers that can absorb water, salt solutions, and other liquids up to several hundred times their weight. Some of these hydrophilic synthetic polymers, such as acrylic acid and its copolymer acrylamide, have been used. The problem is that most of them have low degradability in the soil and accumulate over time. Natural polymers have also been used, like alginate, starch, and xanthan [9,11,13], but the lack of mechanical resistance and high market prices make them unsustainable. Addressing this gap requires sustainable, low-cost, waste-derived organic matrices that couple mechanical robustness with effective nutrient retention and controlled release.

The goal of the present study was to assess the efficiency of matrix-based organomineral fertilizers (OMFs) prepared using waste materials such as biosolids and paper sludge. OMFs are a specific type of slow-release fertilizer (SRF), in which the organic matrix contributes both to nutrient retention and to controlled release. Maize (*Zea mays*) was used as a bioindicator, given its global relevance to food security. These matrices are obtained by functionalizing materials such as biosolids with lignocellulosic materials (paper sludge and sawdust), aiming to enhance biomass growth and nutrient assimilation [15]. This matrix recycles organic matter and facilitates nutrient availability in line with plant demand, thereby reducing environmental losses [16]. When used as a coating, the organic matrix also improves swelling capacity and mechanical resistance [17]. This is achieved by oxidized organic matter bearing negative charges, with carboxylate (R–COO^-) and phenolic (Ph–O^-) groups that promote ion retention [18]. Due to cation exchange capacity, ions are exchanged in soil solution through adsorption processes [19,20] and respond to changes in pH [18,20]. In addition, the water retention capacity is increased by increasing the concentration of cations and water around the organic matrix (adsorbent). This phenomenon is known as a diffuse double layer. It occurs when ions are immobilized on the particle surface by van der Waals forces, chemical bonds, and electrostatic attraction, creating an adsorption layer. These mechanisms allow a greater availability of nutrients in the rhizosphere, reflected in increased biomass in crops [15], while mitigating the environmental impact of water-soluble synthetic fertilizers. These results are relevant because maize is a cornerstone of global food security and is cultivated in subtropical and temperate climates across major producing countries such as Mexico, Brazil, and Ukraine [21].

2. Materials and Methods

2.1. Experimental Conditions and Design

The experiment was conducted during the dry season in the experimental greenhouse of the Faculty of Agrarian and Veterinary Sciences (FCAV), São Paulo State University (UNESP), in Jaboticabal, Brazil (mean temperature 29 °C; altitude 600 m a.s.l.). The experiment was conducted in 5.5 dm^3 plastic pots with a soil characterized by the Athena laboratory as an oxisol (Table 1), with a high content of iron (reddish coloration), density of 1.2 g dm^{-3}, pH 5.2, and base saturation 45%. Soil pH was adjusted to 6.8 with calcium carbonate and magnesium carbonate.

Table 1. Soil properties prior to the experiment (Oxisol). Values correspond to the substrate used in 5.5 dm^3 pots under greenhouse conditions.

Parameter	Value
pH	5.2
Phosphorus, mg dm^{-3}	12
Sulfur (S), mg dm^{-3}	3
Calcium (Ca), mmol dm^{-3}	16
Magnesium (Mg), mmol dm^{-3}	5
Sodium (Na), mmol dm^{-3}	N.D.
Potassium (K), mmol dm^{-3}	1.4
Aluminum (Al)mmol dm^{-3}	N.D.
Organic matter (OM) g dm^{-3}	14
Cation exchange (CEC) meq 100 g^{-1}	40.3
Base saturation, %	45
Iron (Fe_2O_3), hematite g kg^{-1}	192
Density, g dm^{-3}	1.2

Seeds of maize (Zea mays, Poaceae) hybrid variety (Pioneer® brand, Corteva Agriscience, Johnston, IA, USA, 96% purity) were used. Based on maize fertilization requirements at sowing (30 kg ha^{-1} N, 100 kg ha^{-1} P, and 50 kg ha^{-1} K), equivalent per-pot doses were calculated for 5.5 dm^3 pots. Each BC/NPK and BS/NPK pot received 2.0 g of a 4-14-8 formulation (N–P-K), entrapped in 2.0 g of organic matrix and applied once at day 0, whereas each FF pot received 4.0 g of the same uncoated 4-14-8 fertilizer, split into 2.0 g at day 0 and 2.0 g at day 30. The conversion from field to pot scale was performed according to the following equations:

$$\text{Kg ha}^{-1}\ NPK\ pot \times \frac{\text{Kg (4-14-8)}}{\text{Kg ha}^{-1}\ NPK\ field} \tag{1}$$

$$5.5\ \text{dm}^3 \frac{\text{Kg (4-14-8)}}{2 \times 10^6\ \text{dm}^3} \tag{2}$$

The experiment was conducted in a completely randomized design with six replicates per treatment. Four treatments were evaluated: BC (biosolids/cellulose), BS (biosolids/sawdust), FF (uncoated fertilizer without matrix), and NF (control, no fertilizer). The application of FF was divided into two doses at 0 and 30 days after planting, respectively. The experiment lasted 60 days after planting.

Each pot received 2.0 g of the 4-14-8 formulation in the BC and BS treatments, where nutrients were embedded in the respective matrices. In FF, a total of 4.0 g was applied in two equal doses (2.0 g at sowing and 2.0 g at 30 days after sowing). Field-to-pot conversions are shown in Table 2.

2.2. Preparation of Organic Matrix Entrapped NPK Fertilizer

The support materials used in the preparation of the matrices were lignocellulosic residues (residual cellulose from paper sludge), sawdust, and biosolids supplied and characterized by the basic sanitation company of São Paulo State, Monte Alto, Brazil. Because biosolids may contain heavy metals (Cd, Cr, Ni, Pb, and As), they were analyzed by atomic absorption spectroscopy. The supporting material was characterized according to the Colombian technical standard NTC 5167 [22].

Table 2. Fertilization Treatments Summary.

Treatment	Composition	Dose per 5.5-dm^3 pot (g)	Application Schedule (Day After Sowing)
BC Cellulose/biosolids/fertilizer	(1:1) 2.0 g 4-14-8 NPK + 2.0 g cellulose/biosolids matrix	4.0 g formulation	4 × 1.0 g tablets, Day 0
BS Sawdust/biosolids/fertilizer	(1:1) 2.0 g 4-14-8 NPK + 2.0 g sawdust/biosolids matrix	4.0 g formulation	4 × 1.0 g tablets, Day 0
FF (Free Fertilizer)	NPK 4-14-8 (no matrix)	4.0 g NPK fertilizer (no matrix)	2 × 1.0 g tablets, Day 0 + 2 × 1.0 g tablets, Day 30
NF (No Fertilizer)	Oxisol only	N.D.	N.D.

FF: uncoated NPK (4-14-8), fertilizer without organic matrix.

All the materials were dried separately in an oven at 60–70 °C for 3 days, then ground and homogenized using a laboratory grinder and mixer. Biosolids were mixed with cellulose or sawdust in a 3:1 *w*/*w* ratio to obtain the organic matrices. Synthetic fertilizer entrapment was performed at a 1:1 ratio, using 15% commercial saresh (*Acacia* sp. gum) as a binder under continuous agitation for 24 h. The solid mixture was crushed and sieved through a 100-mesh screen for subsequent tableting by compression. Samples were then analyzed physicochemically and microbiologically according to NTC 5167 to confirm sanitization [22].

The pH was measured in a 1:10 OMF/water suspension following EN 13037:2011 [23]; the meter was calibrated with pH 4.01, 7.00 and 10.01 buffers at 25 °C. Organic carbon was determined by the Walkley–Black procedure according to ISO 14235:1998 [24]. Nitrogen, phosphorus, and potassium were determined according to ISO 11261 (TKN) [25], ISO 6878 [26], and FAAS (K, 766.5 nm) [27]. For microbiology, Salmonella detection followed ISO 6579-1:2017 [28], and mesophilic/thermophilic aerobic counts followed ISO 4833-1:2013 [29]. Cation exchange capacity (CEC) was determined using ISO/TS 22171:2023 ISO/TS 22171:2023 [30], and water retention capacity (WRC) was determined according to Gungula et al. [31]. Nitrogen, phosphorus, and potassium were determined according to ISO 18644:2016 [32]. Total coliforms were enumerated following ISO 4831:2006 [33]. Salmonella was detected by plate counts [34]. Mesophiles and thermophiles were determined by plate counts [35].

2.3. Measurement of Biomass Growth and Nutrient Assimilation of Maize (Zea mays) Cultivated in Pots

The fresh weight of different plant parts was recorded 60 days after sowing with an electronic balance. The dry weight of the same tissues was also recorded after drying in a hot-air electric oven at 70 °C for 48 h. The plant height from the base to the insertion of the last leaf, stem diameter, and leaf area were measured with a measuring tape. Similar methodologies have been used in studies where organic matrices improved crop yields [36].

The assimilation of nutrients was determined in the total dry mass. Potassium was measured by atomic emission spectroscopy with a wavelength of 589 nm. Phosphorus was measured by colorimetry at a wavelength of 450 nm in a UV/Visible spectrometer. Ammoniacal and total nitrogen were determined by the Kjeldahl method [37].

2.4. Statistical Treatment of Nutrient Release Data

Data analysis was performed using AGROESTAT version 1.1 (São Paulo State University, Jaboticabal, Brazil), a software package for the statistical analysis of agronomic trials. A one-way analysis of variance (ANOVA) was applied, and treatment means were compared using Tukey's test.

3. Results and Discussion

3.1. Characterization of the Supporting Material

The physicochemical and microbiological parameters obtained from the analysis of the supporting material (feedstock) are presented in Table 3.

Table 3. Physicochemical and microbiological characterization of feedstock (biosolids, cellulose and sawdust.

Parameter	Biosolids	Cellulose	Sawdust
Total nitrogen (N)%	2.46 ± 0.88	0.38 ± 0.50	0.14 ± 0.25
Total phosphorus (P_2O_5), %	2.10 ± 1.29	0.46 ± 0.98	0.20 ± 0.1
Total potassium (K_2O), %	0.64 ± 0.65	N.D.	N.D.
Water retention capacity (WRC), %	112.50 ± 0.03	264 ± 0.08	1.91 ± 0.09
Cation exchange (CEC), meq 100 g^{-1}	35.27 ± 2.03	9.31 ± 0.04	69.7 ± 0.07
Humidity (H), %	59.66 ± 0.58	55.60 ± 0.05	59.4 ± 0.03
pH	7.01 ± 0.48	7.73 ± 0.03	5.91 ± 0.07
Electric conductivity (EC), dS m^{-1}	4.76 ± 0.17	0.02 ± 0.12	7.10 ± 0.017
Organic matter (OM), %	14.64 ± 2.22	22.90 ± 1.20	46.9 ± 1.02
Ashes, %	64.01 ± 2.88	42 ± 0.03	15.5 ± 0.09
Carbon nitrogen ratio C/N,%	6.68 ± 3.20	67 ± 0.06	72.80 ± 0.08
Density, g cm^{-3}	0.48 ± 0.08	0.36 ± 0.008	0.19 ± 0.02
Microbiological parameter			
Mesophiles CFU g^{-1}	9.48×10^{10}	1.3×10^{9}	3.3×10^{10}
Thermophiles CFU g^{-1}	4.52×10^{8}	8.8×10^{8}	8.0×10^{7}
Enterobacteria CFU g^{-1}	1.0×10^{5}	2.0×10^{1}	2.5×10^{1}
Salmonella sp. (absent in 25 g)	N.D.	N.D.	N.D.
Metals			
Na%	0.17± 0.10	N.D.	N.D.
CaO%	3.78 ± 0.317	9.12 ± 0.02	N.D.
MgO%	0.56 ± 0.31	0.24 ± 0.04	N.D.
Zn, ppm	0.39 ± 0.27	N.D.	N.D.
Cr, ppm	381.57 ± 3.0	55.18 ± 0.35	N.D.
Cd, ppm	2.72 ± 2.51	N.D.	N.D.
Pb, ppm	36.98 ± 2.22	N.D.	N.D.
Ni, ppm	149.38 ± 2.88	11.71 ± 0.77	N.D.
As, ppm	0.18 ± 3.20	16.51 ± 0.67	N.D.

ND: Not determined. The calculations of the physicochemical and microbiological variables are made on a dry basis.

The C/N ratios of the feedstocks differed markedly (Table 3), being low in biosolids (6.7) and very high in cellulose (67) and sawdust (72.8). These values indicate contrasting decomposition rates and nutrient release patterns when used as matrices for fertilizer entrapment. Biosolids showed nitrogen and phosphorus contents of 2.46% and 2.10%, respectively. Their cation exchange capacity (CEC) was 35.27 meq 100 g^{-1}, exceeding the minimum requirement of 30 meq 100 g^{-1} established in the Colombian technical standard NTC 5167 [22]. Together with cellulose, biosolids contributed organic matter contents of 14.64% and 22.90%, respectively, values that meet the minimum of 15% required by the same standard.

Organic matter provides oxidized complexes, such as carboxylates (–COO^{-}), which increase CEC [18]. Hydroxyl groups (–OH) in cellulose enhance water retention capacity (WRC). These mechanisms promote the adsorption of exchangeable ions at the solid–liquid interface, contributing to nutrient accumulation in the diffuse double layer and reducing losses by leaching or volatilization, as reported in other studies [19,20]. The WRC values for biosolids (112.50%) and cellulose (264%) were both above 100%, in compliance with NTC 5167 [22], which requires that materials retain at least their own weight in water.

Heavy metal concentrations in the biosolids complied with the thresholds established by the Colombian technical standard NTC 5167 (As 41, Cd 39, Cr 1200, Hg 17, Ni 420, Pb 300 mg kg^{-1}) [22]. According to the USEPA (1999) [38] guidelines, these concentrations were also within the limits required for Class A biosolids. Combined with the microbiological results (absence of Salmonella in 25 g and low levels of enterobacteria), this supports their classification as Type A, suitable for unrestricted agricultural applications. The low C/N ratio of biosolids favored mineralization and nutrient availability, while the high C/N ratios of cellulose and sawdust suggest slower decomposition and potential N immobilization, consistent with their role as structural matrices rather than nutrient sources. These results confirm the suitability of the supporting materials for use in OMFs, which combine adequate nutrient content, CEC, and WRC with compliance with sanitary and legal thresholds.

3.2. Characterization of the Occluded Fertilizers

Table 4 shows the physicochemical and microbiological parameters of the occluded fertilizers: BC/NPK and BS/NPK.

Table 4. Physicochemical and microbiological parameters.

Parameter	BC/NPK	BS/NPK
pH	6.7	6.6
Organic matter (OM), %	17.4	10
Cation exchange (CEC) meq 100 g^{-1}	82.6	76.8
Water retention capacity (WRC)	205	138.5
Carbon nitrogen ratio (C/N)	13.80	7.54
Total nitrogen (N), (%)	4	4
Phosphorus (P), (%)	14	14
Potassium (K), %	8	8
Enterobacteria CFU g^{-1}	9.5×10^2	2.2×10^2
Mesophiles CFU g^{-1}	2.5×10^6	6.4×10^8
Thermophiles CFU g^{-1}	2.4×10^{10}	7.5×10^8

The physicochemical and microbiological parameters of the occluded fertilizers are presented in Table 4. The pH values of BC/NPK (6.7) and BS/NPK (6.6) complied with the acceptable ranges established by NTC 5167 [22]. During the occlusion process, enterobacteria were markedly reduced, from 1.0×10 CFU g^{-1} in the raw materials to 9.5×10^2 CFU g^{-1} in BC/NPK. This reduction has been associated with the crenation of microbial cells caused by the osmotic pressure generated by N, P, and K salts [39].

Compared with BS/NPK, the BC/NPK formulation exhibited higher values of CEC, organic matter, and WRC, reflecting the influence of cellulose on nutrient retention (Table 4). This can be attributed to the presence of deinked paper sludge, which provides oxidized organic functional groups such as carboxylates ($–COO^-$) and hydroxyls (–OH). These groups can form hydrogen bonds and coordination complexes with cations, thereby promoting nutrient retention and gradual release [40]. In contrast, uncoated NPK fertilizers typically display a burst release during early application periods, a phenomenon also well documented in polymer-based controlled release systems [41]. The C/N ratio decreased to 13.8 in BC/NPK, reflecting a higher degree of organic matter decomposition (mineralization). Microbial activity consumes organic compounds, lowering the C/N ratio. A final C/N ratio below 20 is generally considered indicative of maturity and beneficial for soil application [42].

3.3. Biomass Growth of Maize (Zea mays), Under Uncoated NPK and Ma-Trix-Based OMF Treatments

Figures 1 and 2 show the effects of the treatments on maize biomass, expressed as plant height, stem diameter, leaf area, and aerial and root mass.

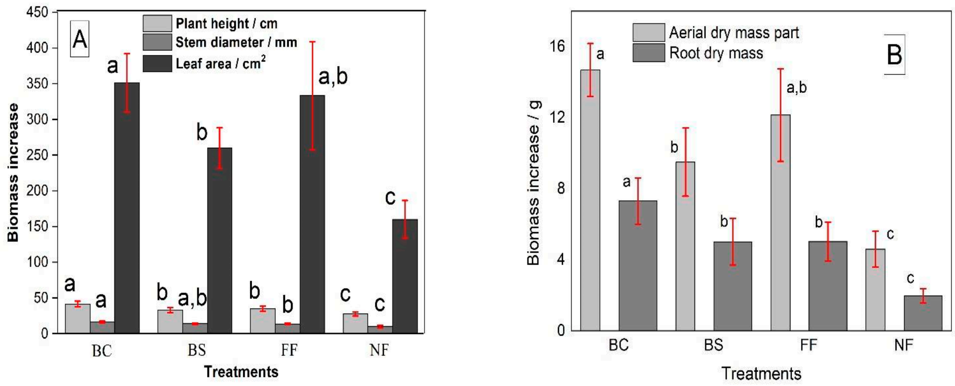

Figure 1. Effect of slow-release organic matrices on increasing biomass of the maize (*Zea may*) model, (**A**): biomass in terms of plant height, stem diameter and leaf area, (**B**): dry biomass in grams. BC: Cellulose/biosolid/fertilizer. BS: Sawdust/biosolid/fertilizer. FF: Free synthetic fertilizer. NF: Without fertilizer. Different letters show significant differences at $p \leq 0.05$.

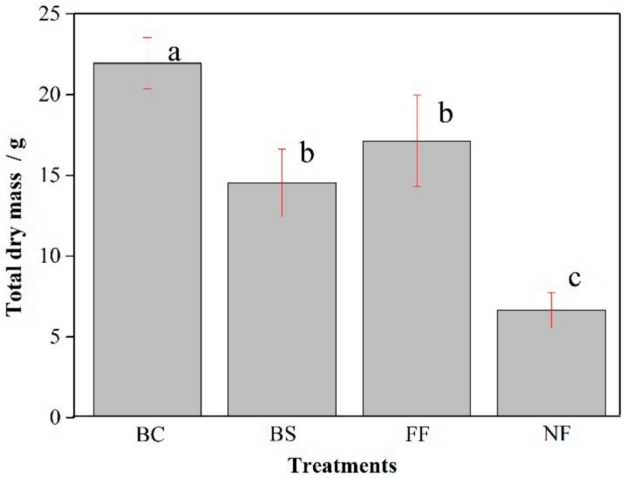

Figure 2. Effect of treatments on total dry mass maize. (*Zea mays*). BC: Cellulose/biosolid/fertilizer. BS: Sawdust/biosolid/fertilizer. FF: Free synthetic fertilizer. NF: Without fertilizer. Different letters show significant differences at $p \leq 0.05$.

According to Figure 1A, the BC treatment produced significantly greater stem diameter and plant height than the other treatments, with differences that were statistically significant. These increases can be attributed to the entrapment of NPK in the cellulose–biosolid matrix. Compared with FF, BC increased plant height by 20.4% and stem diameter by 13.7%. Leaf area showed no significant differences among treatments, indicating that nutrient entrapment did not directly affect this parameter. The BS treatment displayed a trend similar to FF, suggesting that cellulose had a stronger effect on biomass growth than sawdust.

In Figure 1B, root dry mass was significantly higher in the BC treatment than in all others. For aerial dry biomass, BC showed the highest values and was significantly greater than BS, while FF presented intermediate results, not differing from either BC or BS. NF produced the lowest aerial biomass, significantly lower than all other treatments. These results, consistent with the lack of differences in leaf area among fertilized treatments, indicate that the benefits of the cellulose matrix were most evident in root development, although BC also outperformed BS in aerial biomass.

Figure 2 shows that the BC treatment had the highest total dry mass, significantly greater than all other treatments. Specifically, BC increased total biomass by 26.9% compared to FF, 50.3% compared to BS, and more than 100% compared to unfertilized plants (NF). BS and FF did not differ significantly from each other, while NF yielded the lowest values. ANOVA confirmed significant differences among treatments for plant height, stem diameter, leaf area, root dry biomass, and aerial dry mass, except between BS and FF for leaf area and aerial dry biomass.

These results demonstrate that entrapping NPK in the biosolid–cellulose matrix enhanced biomass accumulation more effectively than either the biosolid–sawdust matrix or uncoated fertilizer. Moreover, the improvement observed in plant height, stem diameter, and root biomass with BC highlights the added benefits of the cellulose-based organo-mineral fertilizer. Importantly, BC and BS received a single application of 2.0 g of NPK embedded in the organic matrix, whereas FF was applied in two split doses totaling 4.0 g. Thus, comparable or higher yields were achieved with only half the amount of mineral fertilizer, implying reduced input costs and lower environmental impact.

3.4. Nutrient Assimilation in Maize (Zea mays), Under Uncoated NPK and Ma-Trix-Based OMF Treatments

Figure 3 shows the effect of the BC, BS, FF and NF treatments on the nutrient content (N, P, K) in the total dry mass of maize (*Zea mays*), corresponding to $n = 6$ for each treatment.

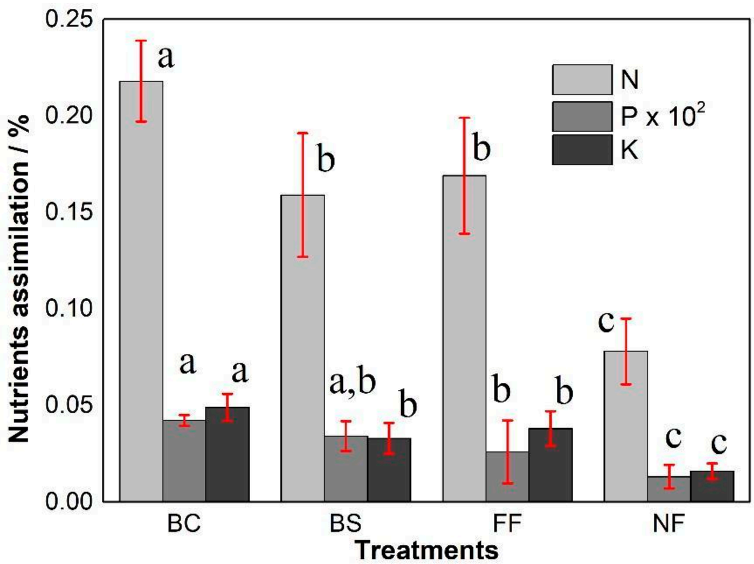

Figure 3. Effect of the BD, BS, FF and NF treatments on nutrient assimilation in the maize model (*Zea mays*). BC: Cellulose/biosolid/fertilizer. BS: Sawdust/biosolid/fertilizer. FF: Free synthetic fertilizer. NF: Without fertilizer. Different letters show significant differences at $p \leq 0.05$.

BC led to significantly greater nutrient assimilation than the other treatments, as indicated by the different letters in Figure 3; BS was more similar to FF than to BC. Differences in nutrient assimilation between BC and FF were 22.5% for N, 38.6% for P, and 22.7% for K. As expected, the assimilation of NPK was significantly higher in plants with fertilizer addition than in plants without fertilizer. The BC formulation allowed for the retention of nutrients as well as their absorption from the soil solution to the root surface, thus improving the efficiency of nutrient supply according to the plant nutritional requirements. This is consistent with other studies using low-cost organic matrices that have increased crop yields [36].

The best yields obtained with BC can be attributed to the contribution of organic matter (OM) from biosolids and pretreated residual cellulose. Delignified cellulose contains more labile OM than sawdust [43,44]. These materials act as colloidal adsorbents that promote root development and increase soil permeability. Their interaction with cations and water leads to the formation of a diffuse double layer [45], thereby enhancing nutrient uptake. Moreover, although the soil used was an Oxisol, typically rich in Fe and Al oxides that restrict P availability, the OM in the biosolid/cellulose matrix likely reduced phosphate fixation. Functional groups such as carboxylates and phenolics can complex Fe^{3+} and Al^{3+} or occupy binding sites on hematite and goethite surfaces, limiting the adsorption of phosphate anions. Similar mechanisms have been reported in highly weathered tropical soils, where oxide surface occupation by organic ligands decreases P immobilization and increases its presence in the soil solution [46–48].

This mechanism may explain the higher P assimilation observed in the BC treatment compared to the uncoated fertilizer. In addition, the water retention capacity of the matrix [17] contributes to its hydrophilicity, allowing absorbed water to be gradually released and taken up by the plant. Furthermore, hydrogen bonds between the cellulose polymeric matrix, water, and fertilizer enable a slow and progressive nutrient release, as the polymer–fertilizer bonds are broken either by hydrolysis or enzymatic action, a mechanism well documented in polymer-based controlled release systems [49]. These combined processes improve the efficiency of nutrient delivery according to crop nutritional requirements.

Figure 4 shows the interaction between roots and the fertilizer entrapment in the matrix biosolid/cellulose after the harvest.

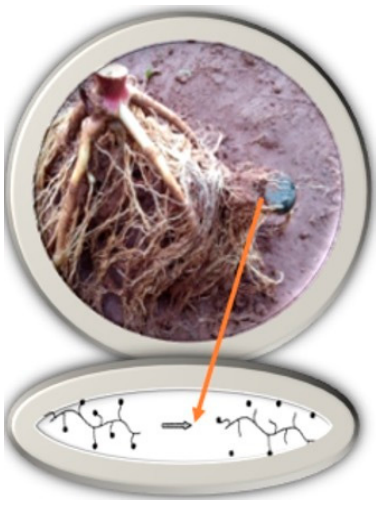

Figure 4. Interaction between pellets of fertilizer entrapment in BC matrix. BC: Cellulose/biosolid/fertilizer.

The BC support material persisted until the end of the crop cycle, maintaining good mechanical resistance 60 days after sowing and showing strong adherence to the roots. This close contact favored nutrient extraction and prevented the type of catastrophic release often observed with coated fertilizers [50]. Around the BC pellets, the liquid phase acted as an adsorbent, where a diffuse double layer of cations and water formed, solvating the ions and enabling their retention and exchange. This mechanism reduced nutrient losses by leaching and ensured a more sustained nutrient supply over time, unlike conventional fertilizer, which was washed away and did not remain in the soil [51]. Figure 5 illustrates the effects of the different treatments on maize root development.

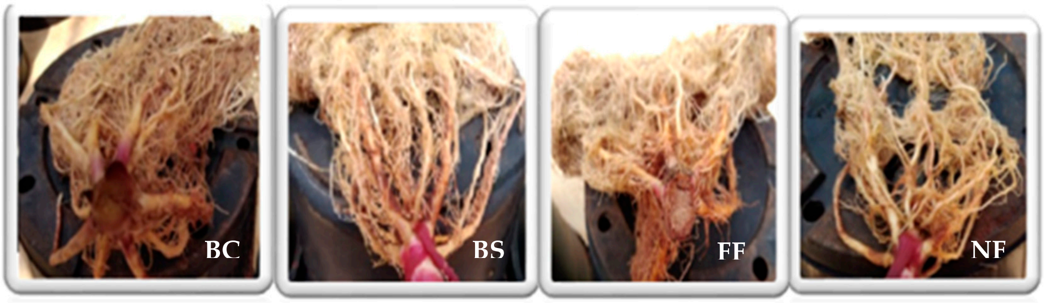

Figure 5. Morphological changes in roots with different treatments. BC: Cellulose/biosolid/fertilizer. BS: Sawdust/biosolid/fertilizer. FF: Free synthetic fertilizer. NF: Without fertilizer.

Roots grown with the BC treatment were visibly larger than those under FF, BS, or NF, consistent with the significantly higher assimilation of nitrogen (NH), phosphorus (HPO_4^{2-}), and potassium (K^+) measured in Figure 3, and with their subsequent transport to aboveground tissues. This enhanced nutrient supply promoted root growth and overall plant development. As a slow-release fertilizer, BC provides N in a form that delays its immediate availability, reducing the need for multiple applications [15,16] and lowering NH concentrations in surface water and soil solution [52,53], thereby minimizing losses through ammonia volatilization [52,54].

Therefore, the BC acts as a reservoir for the maize crop, supplying it with nutrients according to its nutritional needs, becoming a promising resource for the formulation of slow-release fertilizers as it can reduce the fertilizer cost per hectare [55]. The organic matter in the matrix also improves soil quality, enabling crops to respond better to variations in pH, temperature, and moisture [56], while conventional fertilizers increase soil salinity and acidity [3]. Moreover, delignified paper sludge combined with nitrogen-rich residues such as poultry manure or sewage sludge further enhances microbial activity and nutrient cycling [57,58]. This bioassay showed that organo-mineral fertilizers like BC (a form of SRF) favored nutrient assimilation, reduced leaching and volatilization losses, and improved root growth and plant height, giving them clear advantages over conventional fertilizers.

Trapping mineral fertilizer in a low-cost, environmentally friendly organic matrix significantly improved NPK delivery and maize yield. Modification of the microenvironment around the BC granules enhanced nutrient uptake and use efficiency, ensuring that nutrients were released and absorbed in accordance with the plant's nutritional requirements. Despite the good performance obtained, further evaluation of BC/NPK under field conditions is required, given the short growing period and limited soil volumes used in these experiments. Studies should extend to the production stage to determine seed number per plant and seed weight. This technology has the potential to generate economic benefits for farmers, as the fertilizer can be applied at half the usual dose, while significantly reducing environmental impacts by limiting the excessive use of mineral fertilizers. Therefore, it can be considered a strong alternative to conventional fertilizers, which are associated with serious economic, environmental, and health problems.

This bioassay focused on plant growth and nutrient assimilation as primary indicators of fertilizer performance, consistent with standard practice in initial assessments of slow-release fertilizers (SRFs), including organo-mineral fertilizers (OMFs) [59–61]. Future research should complement plant-based indicators with soil chemistry and microbial community analyses (e.g., phospholipid fatty acid analysis profiling or high-throughput sequencing). Previous studies have demonstrated that OMFs can influence soil properties and microbial activity [62,63], underscoring the importance of integrating these dimensions in field evaluations.

4. Conclusions

The bioassay with *Zea mays* showed that entrapping mineral fertilizer in a biosolid/cellulose matrix (BC) enhanced nutrient assimilation, root development, leaf area, and plant height, resulting in 28.4% higher biomass compared to the free uncoated fertilizer (FF) treatment. Compared with FF, BC/NPK increased plant nutrient uptake by 22.5% (N), 38.6% (P), and 22.7% (K), indicating a more regulated nutrient release and improved availability in the rhizosphere.

These outcomes can be attributed to the stabilizing role of pretreated cellulose, which increased hydrophilicity, water retention, and cation exchange capacity, enabling a more regulated release of nutrients and greater biomass 60 days after sowing.

Although results were obtained under greenhouse conditions and over a short cultivation period, they provide evidence that matrix-based organo-mineral fertilizers represent a promising sustainable alternative. Incorporating conventional fertilizers into organic matrices such as BC can reduce application rates, lower production costs, and mitigate the environmental impacts of excessive mineral fertilizer use. Field-scale, multi-season trials across different soils are required to validate yield responses and assess long-term agronomic and economic benefits.

Author Contributions: R.R.P. carried out experiments, constructed the figures, and drafted the manuscript. W.J.M., A.M.S.R. and A.S.F.A. supervised the experiments in Brazil. C.A.P.J. and N.R.-S. designed the experiments, and edited and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. Internal support was provided by Molecular Studies Interdisciplinary Research Group of Antioquia University (GIEM) (institutional funds; no external grant identifier applies).

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: R.R.P. would also like to acknowledge the support of the Molecular Studies Interdisciplinary Research Group.

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

Abbreviations

Abbrev.	**Meaning**
dw	dry-weight basis
OM	organic matter
TOC	total organic carbon
TKN	total Kjeldahl nitrogen
TP	total phosphorus
AAS/FAAS	(Flame) atomic absorption spectrometry
CEC	cation-exchange capacity
WRC	water-retention capacity (used consistently; replaces legacy CRA)
XRD	X-ray diffraction
SRF	slow-release fertilizer
F	uncoated (mineral) fertilizer
FOMI/FOMII	functionalized organic matrices I/II
LOD/LOQ	limit of detection/quantification
CI	confidence interval
ANOVA	analysis of variance

References

1. Margulis, M.E.; Hopewell, K.; Qereshniku, E. Food, famine and the free trade fallacy: The dangers of market fundamentalism in an era of climate emergency. *J. Peasant. Stud.* **2023**, *50*, 215–239. [CrossRef]
2. Penuelas, J.; Coello, F.; Sardans, J. A better use of fertilisers is needed for global food security and environmental sustainability. *Agric. Food Secur.* **2023**, *12*, 9. [CrossRef]
3. Gómez-Sagasti, M.T.; Alkorta, I.; Becerril, J.M.; Epelde, L.; Anza, M.; Garbisu, C. Microbial monitoring of the recovery of soil quality during heavy metal phytoremediation. *Water Air Soil Pollut.* **2012**, *223*, 3249–3262. [CrossRef]
4. Kakar, K.; Xuan, T.D.; Noori, Z.; Aryan, S.; Gulab, G. Effects of organic and inorganic fertiliser application on growth, yield, and grain quality of rice. *Agriculture* **2020**, *10*, 544. [CrossRef]
5. Deng, A.N.; Luo, J.H.; Su, C.L.; Wu, X.F.; Zhao, M. Reduced inorganic fertiliser in combination with an alkaline humic acid fertiliser amendment on acid growth media properties and cherry tomato growth. *N. Z. J. Crop. Hortic. Sci.* **2021**, *49*, 225–242. [CrossRef]
6. Bajpai, A.K.; Giri, A. Swelling dynamics of a macromolecular hydrophilic network and evaluation of its potential for controlled release of agrochemicals. *React. Funct. Polym.* **2002**, *53*, 125–141. [CrossRef]
7. Menegat, S.; Ledo, A.; Tirado, R. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. *Sci. Rep.* **2022**, *12*, 18773. [CrossRef]
8. Kusin, F.M.; Akhir, N.I.M.; Mohamat-Yusuff, F.; Awang, M. The impact of nitrogen fertiliser use on greenhouse gas emissions in an oil palm plantation associated with land use change. *Atmosfera* **2015**, *28*, 243–250. [CrossRef]
9. Dong, Z.; Qu, N.; Jiang, Q.; Han, Z.; Sun, L.; Zhang, T.; Liang, D.; Shi, Y.; Cheng, Z. Preparation and properties of multifunctional eco- friendly slow-release urea fertiliser encapsulated by diatomite filter aid waste-based superabsorbent. *Prog. Org. Coat.* **2023**, *183*, 107747. [CrossRef]
10. He, Y.; Wu, Z.; Tu, L.; Han, Y.; Zhang, G.; Li, C. Encapsulation and characterization of slow-release microbial fertiliser from the composites of bentonite and alginate. *Appl. Clay Sci.* **2015**, *109–110*, 68–75. [CrossRef]
11. Duan, Q.; Jiang, S.; Chen, F.; Li, Z.; Ma, L.; Song, Y.; Yu, X.; Chen, Y.; Liu, H.; Yu, L. Fabrication, evaluation methodologies and models of slow-release fertilisers: A review. *Ind. Crops Prod.* **2023**, *192*, 116075. [CrossRef]
12. Liang, R.; Liu, M. Preparation and properties of coated nitrogen fertiliser with slow release and water retention. *Ind. Eng. Chem. Res.* **2006**, *45*, 8610–8616. [CrossRef]
13. Salimi, M.; Channab, B.E.; Zahouily, M. A comprehensive review on starch: Structure, modification, and applications in slow/controlled-release fertilisers in agriculture. *Carbohydr. Polym.* **2023**, *322*, 121154. [CrossRef]
14. Tomaszewska, M.; Jarosiewicz, A.; Karakulski, K. Physical and chemical characteristics of polymer coatings in CRF formulation. *Desalination* **2002**, *146*, 319–323. [CrossRef]
15. Dimkpa, C.O.; Fugice, J.; Singh, U.; Lewis, T.D. Development of fertilisers for enhanced nitrogen use efficiency—Trends and perspectives. *Sci. Total Environ.* **2020**, *731*, 139113. [CrossRef]
16. Wise, K.; Selby-Pham, J.; Simovich, T.; Gill, H. Enhancement of capsicum (*Capsicum annuum* L.) functional food value through nutrient supplementation with a biostimulant complex comprising triacontanol, phosphate, and potassium. *N. Z. J. Crop. Hortic. Sci.* **2023**, *53*, 202–213. [CrossRef]
17. Chantigny, M.H. Dissolved and water-extractable organic matter in soils: A review on the influence of land use and management practices. *Geoderma* **2003**, *113*, 357–380. [CrossRef]
18. Calabi-Floody, M.; Medina, J.; Rumpel, C.; Condron, L.M.; Hernandez, M.; Dumont, M.; de la Luz Mora, M. Smart fertilisers as a strategy for sustainable agriculture. *Adv. Agron.* **2018**, *147*, 119–157. [CrossRef]
19. Prakash, K.; Sridharan, A.; Philip, J. Influence of dielectric constant of pore fluids on double-layer swelling: A validation study. *Indian Geotech. J.* **2022**, *52*, 174–180. [CrossRef]
20. Ramadan, B.S.; Sari, G.L.; Rosmalina, R.T.; Effendi, A.J.; Hadrah. An overview of electrokinetic soil flushing and its effect on bioremediation of hydrocarbon contaminated soil. *J. Environ. Manag.* **2018**, *218*, 309–321. [CrossRef] [PubMed]
21. Prasad, R.; Gunn, S.K.; Rotz, C.A.; Karsten, H.; Roth, G.; Buda, A.; Stoner, A.M.K.; Rutherford, S. Projected climate and agronomic implications for maize production in the Northeastern United States. *PLoS ONE* **2018**, *13*, e0198623. [CrossRef]
22. *NTC 5167*; Productos Orgánicos Utilizados Como Abonos o Fertilizantes y Enmiendas de Suelos. Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC): Bogotá, Colombia, 2011.
23. *EN 13037:2011*; Soil Improvers and Growing Media—Determination of pH. CEN: Brussels, Belgium, 2011. Available online: https://www.cen.eu/ (accessed on 22 September 2024).
24. *ISO 14235:1998*; Soil Quality—Determination of Organic Carbon by Sulfochromic Oxidation (Walkley–Black). ISO: Geneva, Switzerland, 1998. Available online: https://www.iso.org/ (accessed on 22 September 2024).
25. *ISO 11261:1995*; Soil Quality—Determination of Total Nitrogen—Modified Kjeldahl Method. ISO: Geneva, Switzerland, 1995. Available online: https://www.iso.org/ (accessed on 22 September 2024).

26. *ISO 6878:2004*; Water Quality—Determination of Phosphorus—Ammonium Molybdate Spectrometric Method. ISO: Geneva, Switzerland, 2004. Available online: https://www.iso.org/ (accessed on 22 September 2024).
27. APHA; AWWA; WEF. Method 3111: Metals by Flame Atomic Absorption Spectrophotometry. In *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; APHA: Washington, DC, USA, 2017. Available online: https://www.standardmethods.org/ (accessed on 22 September 2024).
28. *ISO 6579-1:2017*; Microbiology of the Food Chain—Horizontal Method for the Detection, Enumeration and Serotyping of Salmonella—Part 1: Detection of *Salmonella* spp. ISO: Geneva, Switzerland, 2017. Available online: https://www.iso.org/ (accessed on 22 September 2024).
29. *ISO 4833-1:2013*; Microbiology of the Food Chain—Horizontal Method for the Enumeration of Microorganisms—Part 1: Colony Count at 30 °C by the Pour Plate Technique. ISO: Geneva, Switzerland, 2013. Available online: https://www.iso.org/ (accessed on 22 September 2024).
30. *ISO/TS 22171:2023*; Soil Quality—Determination of Potential Cation Exchange Capacity (CEC) and Exchangeable Cations Buffered at pH 7, Using a Molar Ammonium Acetate Solution. International Organization for Standardization: Geneva, Switzerland, 2023.
31. Gungula, D.T.; Andrew, F.P.; Joseph, J.; Kareem, S.A.; Barminas, J.T.; Adebayo, E.F.; Saddiq, A.M.; Tame, V.T.; Dere, I.; Ahinda, W.J.; et al. Formulation and characterization of water retention and slow-release urea fertiliser based on Borassus aethiopum starch and Maesopsis eminii hydrogels. *Results Mater.* **2021**, *12*, 100223. [CrossRef]
32. *ISO 18644:2016*; Fertilizers and Soil Conditioners—Controlled-Release Fertilizer—General Requirements. International Organization for Standardization: Geneva, Switzerland, 2016.
33. *ISO 4831:2006*; Microbiology of Food and Animal Feeding Stuffs—Horizontal Method for the Detection and Enumeration of Coliforms—Most Probable Number Technique. International Organization for Standardization: Geneva, Switzerland, 2006.
34. Jechalke, S.; Schierstaedt, J.; Becker, M.; Flemer, B.; Grosch, R.; Smalla, K.; Schikora, A. *Salmonella* establishment in agricultural soil and colonization of crop plants depend on soil type and plant species. *Front. Microbiol.* **2019**, *10*, 967. [CrossRef]
35. Maturin, L.; Peeler, J.T. Aerobic Plate Count. In *Bacteriological Analytical Manual*; US Food and Drug Administration: Washington, DC, USA, 2001; pp. 1–11.
36. Deeks, L.K.; Chaney, K.; Murray, C.; Sakrabani, R.; Gedara, S.; Le, M.S.; Tyrrel, S.; Pawlett, M.; Read, R.; Smith, G.H. A new sludge-derived organo-mineral fertiliser gives similar crop yields as conventional fertilisers. *Agron. Sustain. Dev.* **2013**, *33*, 539–549. [CrossRef]
37. Lang, C.A. Simple microdetermination of Kjeldahl nitrogen in biological materials. *Anal. Chem.* **1958**, *30*, 1692–1694. [CrossRef]
38. *EPA 530-R-99-009*; Biosolids Generation, Use and Disposal in the United States. United States Environmental Protection Agency: Washington, DC, USA, 1999.
39. Yaganza, E.S.; Tweddell, R.J.; Arul, J. Osmotic stress, crenation and death of *Erwinia* carotovora subsp. atroseptica caused by inorganic salts. *Appl. Environ. Microbiol.* **2009**, *75*, 4659–4665.
40. Shatruk, M.; Avendano, C.; Dunbar, K.R. Cyanide-Bridged Complexes of Transition Metals: A Molecular Magnetism Perspective. *Prog. Inorg. Chem.* **2009**, *56*, 171–332. [CrossRef]
41. Ebube, N.K.; Jones, A.B. Sustained release of acetaminophen from a heterogeneous mixture of two hydrophilic non-ionic cellulose ether polymers. *Int. J. Pharm.* **2004**, *272*, 11–18. [CrossRef] [PubMed]
42. Mahapatra, D.M.; Kalamdhad, A.S.; Kazmi, A.A. Assessment of compost maturity-stability indices and recent development of composting bin. *Energy Nexus* **2022**, *6*, 100062. [CrossRef]
43. Fierro, V.; Muñiz, G.; Celzard, A.; Furdin, G. Activation of delignified cellulosic material by heat treatment and its application for the removal of dyes from aqueous solution. *J. Chem. Technol. Biotechnol.* **2000**, *75*, 1–7.
44. Filiatrault, M.; D'Acremont, L.; Gendron, R.; Laroche, G. Delignified lignocellulosic fibres as promising carriers for controlled release of biomolecules. *Mater. Sci. Eng. C* **2018**, *82*, 11–18. [CrossRef]
45. Jin, X.; Zhang, Z.; Sun, M.; Wang, L.; Chen, Y.; Zhang, X. Charge distribution and diffuse double layer in a membrane filtration system: A theoretical and experimental study. *J. Colloid. Interface Sci.* **2020**, *574*, 158–167. [CrossRef]
46. Weihrauch, C.; Opp, C. Ecologically relevant phosphorus pools in soils and their dynamics: The story so far. *Geoderma* **2018**, *325*, 183–194. [CrossRef]
47. Touhami, D.; McDowell, R.W.; Condron, L.M. Role of organic anions and phosphatase enzymes in phosphorus acquisition in the rhizospheres of legumes and grasses grown in a low phosphorus pasture soil. *Plants* **2020**, *9*, 1185. [CrossRef] [PubMed]
48. Menezes-Blackburn, D.; Giles, C.; Darch, T.; George, T.S.; Blackwell, M.; Stutter, M.; Shand, C.; Lumsdon, D.; Cooper, P.; Wendler, R.; et al. Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: A review. *Plant and Soil.* **2018**, *427*, 5–16. [CrossRef]
49. Thambiliyagodage, C.; Jayanetti, M.; Mendis, A.; Ekanayake, G.; Liyanaarachchi, H.; Vigneswaran, S. Recent Advances in Chitosan-Based Applications—A Review. *Materials* **2023**, *16*, 2073. [CrossRef]
50. Azeem, B.; KuShaari, K.; Man, Z.B.; Basit, A.; Thanh, T.H. Review on materials and techniques for controlled release fertiliser. *J. Control. Release* **2014**, *181*, 11–21. [CrossRef]

51. Vejan, P.; Khadiran, T.; Abdullah, R.; Ahmad, N. Controlled release fertiliser: A review on developments, applications and potential in agriculture. *J. Control. Release* **2021**, *339*, 321–334. [CrossRef]
52. Xu, J.; Peng, S.; Yang, S.; Wang, W. Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements. *Agric. Water Manag.* **2012**, *104*, 184–192. [CrossRef]
53. Lawrencia, D.; Wong, S.K.; Low, D.Y.S.; Goh, B.H.; Goh, J.K.; Ruktanonchai, U.R.; Soottitantawat, A.; Lee, L.H.; Tang, S.Y. Controlled release fertilisers: A review on coating materials and mechanism of release. *Plants* **2021**, *10*, 238. [CrossRef]
54. Tian, G.; Gao, L.; Kong, L.; Hu, X.; Zhang, J. Ammonia volatilization losses from urea application influenced by rice straw biochar. *Soil. Sci. Plant Nutr.* **2017**, *63*, 525–533.
55. Abdel-Aziz, H.M.M.; Hasaneen, M.N.A.; Omer, A.M. Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Span. J. Agric. Res.* **2016**, *14*, e0902. [CrossRef]
56. Jiang, J.; Wang, Y.; Liang, Y.; Li, L.; Cao, C.; Li, F. Long-term effects of organic manure and inorganic fertilisation on sustainability and chemical soil quality indicators of soybean–wheat cropping system in the Indian mid- Himalayas. *Agric. Ecosyst. Environ.* **2018**, *257*, 38–46. [CrossRef]
57. Charest, M.H.; Beauchamp, C.J. Composting of de-inking paper sludge with poultry manure at three nitrogen levels using mechanical turning: Behavior of physico-chemical parameters. *Bioresour. Technol.* **2002**, *81*, 7–17. [CrossRef]
58. Gea, T.; Barrena, R.; Artola, A.; Sánchez, A. Monitoring the biological activity of the composting process: Oxygen uptake rate (OUR), respirometric index (RI), and respiratory quotient (RQ). *Biotechnol. Bioeng.* **2004**, *88*, 520–527. [CrossRef]
59. Sitzmann, T.J.; Sica, P.; Zavattaro, L.; Moretti, B.; Grignani, C.; Oberson, A. An isotope study on nitrogen and phosphorus use efficiency and movement in agricultural systems. *Agrosystems Geosci. Environ.* **2024**, *7*, e20473. [CrossRef]
60. Disciglio, G.; Tarantino, A.; Frabboni, L. Yield and fruit characteristics of tomato crops grown with mineral macronutrients: Impact of organo-mineral ferti-lizers through foliar or soil applications. *Plants* **2024**, *13*, 1458. [CrossRef]
61. Srinivasarao Ch Naik, M.R.; Naorem, A.; Chandana, M.; Baral, K. Organo-mineral fertilizers for sustainable agriculture. *Indian J. Fert.* **2024**, *20*, 366–383.
62. Plaza, C.; Giannetta, B.; Fernández, J.M.; López-de-Sa, E.G.; Polo, A.; Gascó, G.; Méndez, A.; Zaccone, C.; Shotbolt, L.; Fernández-Getino, A.M.; et al. Soil organic matter: A key player in soil quality and a major constraint for global food security. *J. Environ. Manag.* **2019**, *245*, 118–127. [CrossRef]
63. Zhou, J.; Sun, R.; Li, Y.; Wang, X.; Zheng, Y.; Zhu, H.; Wang, C.; Liu, Y.; Zhang, J.; Chen, L.; et al. Long-term application of an organo-mineral fertiliser improves soil microbial community structure and enzyme activities in a maize cropping system. *Agric. Ecosyst. Environ.* **2022**, *338*, 108398.