Available online at http://scik.org
Commun. Math. Biol. Neurosci. 2026, 2026:18
https://doi.org/10.28919/cmbn/9727
ISSN: 2052-2541

TRANSFORMATION OF PELLET-BASED PLANTING MEDIA AS AN ORGANIC MATTER AND NUTRIENT ENHANCER FOR IMPROVING SOIL QUALITY

DIAN PRATAMA PUTRA[1,*], NANDA SATYA NUGRAHA[2], MOHAMMAD PRASANTO BIMANTIO[3], TEDDY SUPARYANTO[3,4], KUNCAHYO SETYO NUGROHO[4], BENS PARDAMEAN[4,5]

[1]Faculty of Agriculture, Institute of Agriculture STIPER, Yogyakarta 55281, Indonesia
[2]Faculty of Forestry, Institute of Agriculture STIPER, Yogyakarta 55281, Indonesia
[3]Faculty of Agricultural Technology, Institute of Agriculture STIPER, Yogyakarta 55281, Indonesia
[4]Bioinformatics and Data Science Research Center, Bina Nusantara University, Jakarta 11480, Indonesia
[5]Computer Science Department, BINUS Graduate Program - Master of Computer Science, Bina Nusantara University, Jakarta 11480, Indonesia

Abstract: Soil degradation driven by excessive inorganic fertilizer use and conventional cultivation practices has reduced land productivity in tropical regions, including Indonesia. This study developed biological pellet-based planting media to improve soil physical, chemical, and biological properties while providing controlled nutrient release. The research employed a panel design and split-plot layout on sandy Entisol soils, evaluating physical–chemical characteristics, rhizosphere microbial colonization, and nutrient-release kinetics using the Gompertz model. The results show that pellets increased soil porosity up to 56%, extended water retention to 22 hours, and significantly enhanced organic carbon as well as N, P, K, Ca, and Mg levels compared with the control. Nutrient release followed a lag–exponential–plateau pattern, indicating an efficient gradual-release mechanism. Microbial and soil-fauna activity more than doubled, demonstrating restored biological functioning of the soil. Treatments with a balanced organic–inorganic ratio (50:50) exhibited the best overall performance across all parameters. Overall, pellet-based planting media prove effective as multifunctional soil conditioners that enhance fertility, nutrient efficiency, and agroecosystem sustainability in marginal tropical soils.

[*]Corresponding author
E-mail address: dianswn@instiperjogja.ac.id
Received December 03, 2025

Keywords: soil degradation; soil fertility; Gompertz model; bio-pellets; nutrient release.
2020 AMS Subject Classification: 92C80, 92D40, 65C20.

1. INTRODUCTION

Food sovereignty and the sustainability of agricultural production systems now demand a paradigm shift from intensification that relies solely on inorganic inputs toward a model that integrates soil engineering, soil biology, and ecosystem-oriented agronomic practices. Indonesia, with its diverse agroclimatic conditions, faces a serious challenge of large-scale land degradation, characterized by declining soil organic matter, reduced soil biota activity, and changes in soil structure and porosity that affect water retention and nutrient accessibility for plant roots. This condition requires solutions that are not only technical but also contextual, respecting the socio-economic dynamics of farmers and offering technological packages that are easily adaptable [1].

Digital innovations in agriculture, ranging from web-based platforms for managing genetic diversity data to deep-learning driven automation systems are increasingly shaping how agronomic decisions are made in modern production landscapes [2–4]. Best practices in agricultural information systems further emphasize that integrating digital tools with land-management strategies strengthens knowledge flow and supports farmer-level innovation [5].

Biological planting media in pellet form serve as an integrated intervention, offering a combination of organic materials, minerals, and microorganisms that provide dual functions: structured nutrient supplementation and restoration of soil ecosystem services through enhanced biological activity. The concept of pelletization enables controlled nutrient release, minimizes losses through leaching or volatilization, and maintains the viability of beneficial microbes within the rhizosphere. Pellets formulated with appropriate compositions can also improve the physical properties of the planting media, increase cation exchange capacity, stabilize soil aggregates, and enhance pore structure to facilitate root penetration and water movement [6, 7].

Preliminary observations suggest that pellets can effectively improve the physical, chemical, and biological properties of soil under tropical field conditions, influence nutrient-release patterns that interact with in-soil nutrient dynamics, and determine the extent to which microbial colonization from pellets modifies local microbial communities and ecosystem services related to nutrient cycling. Broadly, this study aims to examine the effects of pellet transformation as a planting medium on land quality improvement [8, 9]. Specifically, the research objectives are: (1) to evaluate changes in soil physical properties (porosity, permeability, and water-holding retention) based on X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM) observations after pellet application, (2) to measure changes in soil chemical properties including pH, availability of N, P, K, Ca, Mg, and C-organic content, (3) to observe colonization patterns of microorganisms (bacteria and fungi) from pellets into the rhizosphere environment and their effects on the presence of earthworms, and (4) to analyze the kinetics of nutrient release from the pellet media.

Restoring soil fertility requires a multi-dimensional approach that recognizes soil as a living system. Soil organic matter is the central driver of soil dynamics, serving as a substrate for microbes, influencing aggregate formation, and functioning as a chemical buffer that determines nutrient availability [10, 11]. The pellets developed in this study are intended as a localized source of organic matter that provides a measured nutrient supply and carbon sources for microorganisms. Controlled-release theory explains that the physical structure of pellets and the characteristics of their matrix determine nutrient-release kinetics, while biological interactions such as microbial enzymatic activity and biofilm formation mediate chemical transformations that influence the forms of nutrients available to plant roots.

2. RESEARCH METHODOLOGY

The study was conducted over five months, from May 2025 to September 2025, during the lowest rainfall season (<60 mm). The research site was located in Srandakan District, Bantul Regency, Yogyakarta Province, Indonesia, at the coordinates (-7.9585258, 110.2478838). The location was selected to represent heterogeneous marginal land conditions characterized by sandy Entisol soils, classified as United States Department of Agriculture (USDA) Typic Quartzipsamment, siliceous, and isohyperthermic. These soils are derived predominantly from silica (quartz), exhibit consistently high temperatures (>22°C year-round), and are situated within a dry tropical coastal zone with a maximum distance of 40 km from the shoreline.

The experimental design employed a split-plot randomized complete block design (RCBD) combined with a Panel Design to monitor temporal changes within the same land units, allowing observation of soil fertility dynamics and microbial community shifts over time. The applied treatments consisted of two main pellet formulations [12, 13], namely Organic Pellets and Inorganic Pellets, which were distributed across four treatment groups as presented in Table 1. A total of 100 kilograms of material was prepared and applied to a 100 m² frame, followed by daily irrigation. The field interpretation and placement of sampling points for each treatment plot were carried out based on the layout illustrated in Figure 1.

TABLE 1. Composition of pellet-based treatments.

Treatment	Organics Pellets (%)	Inorganic Pellets (%)	Description
A (Control)	0	0	100% NPK (Control)
B (25:75)	25	75	Organic pellets + inorganic pellets
C (50:50)	50	50	Balanced organic – inorganic pellets
D (75:25)	75	25	High-organic pellet mixture

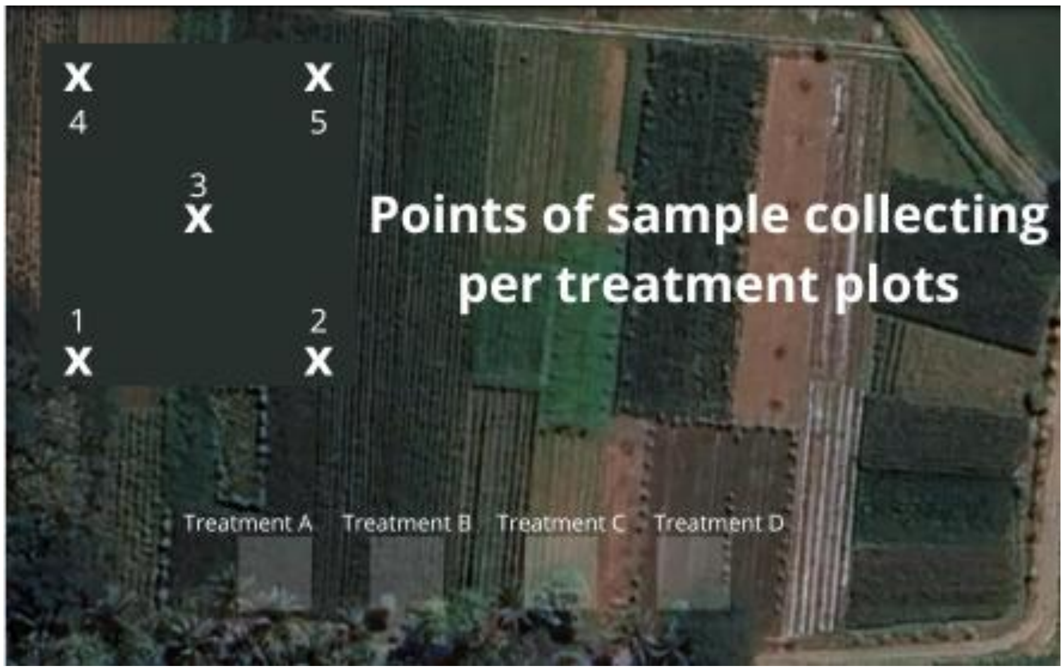

FIGURE 1. Model performance trend across multiple horizons, measured by (A) RMSE and (B) R^2.

The total field area used was 1000 m² to characterize how each treatment performed under realistic field conditions, ensuring representativeness with respect to the intended raw material configurations. The raw materials for pellet production consisted of two primary formulations: organic pellets and inorganic pellets. Organic pellets were produced using a mixture of lignin-rich biomass (peanut shells), rice-husk biochar, composted goat manure, crushed eggshells as a calcium source, and local microbial inoculum. In contrast, inorganic pellets were formulated using bentonite/zeolite, nutrient elements with a purity of approximately ±75% [14, 15], technosol soil, and a liquid carrier that functioned as both a binder and a filler [10].

The production process involved grinding all materials using a disk mill to a particle size of approximately 0.5 mm, followed by initial low-temperature oven-drying (≤90° C) for 12 hours to ensure microbial safety and pathogen reduction. A 24-hour parametric composting phase was conducted to activate microbial communities, after which the mixture was dried and pelletized using a KL210 pelletizer. After shaping, the pellets were briefly air-dried and coated with microbial inoculum [10] using a Very Low Volume (VLV) sprayer to ensure even distribution of beneficial microbial cultures on the pellet surface. The inorganic pellets were designed as a mineral matrix, processed using a pressed mill to break down aggregates before pellet shaping and drying. Pellet size and dimensions were optimized to maximize effective surface area, enabling controlled modulation of nutrient-release kinetics.

3. Results

The transformation of planting media into pellet form produced clear improvements in the physical, chemical, and biological properties of the soil, consistent with the conceptual framework outlined in the previous sections. Increases in porosity, aggregate stability, and water retention indicate that the engineered pellet structure effectively enhances soil aeration and moisture dynamics [16]. Chemically, elevated levels of organic carbon and macro-nutrient availability reflect a controlled and sustained nutrient-release pattern. At the same time, biologically, the enhanced microbial colonization and greater soil fauna activity demonstrate the recovery of soil ecosystem functions as a living and adaptive system. These findings reinforce the hypothesis that pellet-based planting media function dually as soil amendments and as sources of biological nutrients, integrating material engineering, soil biology, and sustainable agronomic principles [7, 9, 10].

3.1. Chemical Properties. Figure 2 presents the changes in macro-nutrient contents (N, P, K, Ca, Mg) and several soil or planting-media parameters (organic matter, C/N ratio, pH, micronutrients, and unknown materials) across the four pellet-based treatments: Treatment A (NPK control), Treatment B (25:75), Treatment C (50:50), and Treatment D (75:25). With respect to nitrogen (N%), the control (A) exhibited the lowest value (approximately 1.4%), whereas the pellet treatments showed substantial increases, reaching up to ±8.85% in one of the treatments. This indicates that pellet media containing specific mixed ratios beyond NPK alone can effectively increase total nitrogen content in the planting media. Similarly, relative increases in P and K were observed. However, the absolute values of K remained low in several treatments, demonstrating that the addition of pellet media can noticeably alter macro-nutrient profiles [17].

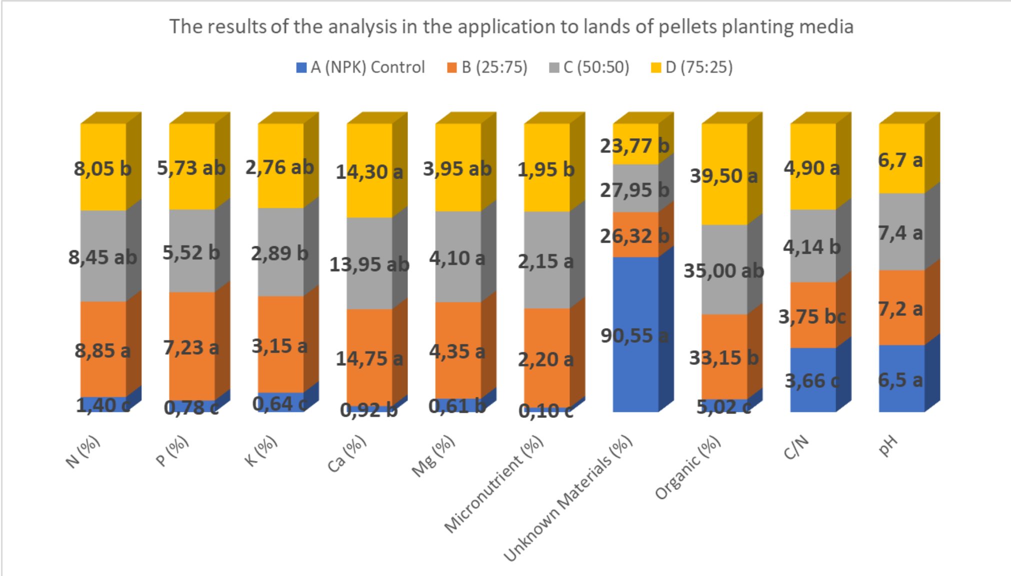

FIGURE 2. Chemical and nutrient composition of the planting media across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25), showing changes in macronutrients (N, P, K, Ca, Mg), micronutrients, unknown materials, organic matter, C/N ratio, and pH following pellet application.

The behavior of calcium (Ca) and magnesium (Mg) is also notable, treatments with higher mixed ratios showed increases of 14.75% in Ca and 4.35% in Mg in one treatment, far exceeding the control. This suggests that pellet media incorporating targeted supplementary components can significantly enhance the medium's capacity to supply Ca and Mg [14].

Parameters that are not always the primary focus, such as organic matter, C/N ratio, and pH also demonstrated relevant dynamics. One treatment showed a remarkably high proportion of unknown materials (90.55%) compared with only 5.02% organic matter in the control, indicating that pellet-amended media may contain substantially richer organic fractions or reflect markedly different material compositions. The C/N ratio also varied widely, from 3.66% to 33.15% across treatments. This is important because the C/N ratio directly influences nitrogen mineralization and nutrient availability. Soil pH ranged from approximately 6.5 to 7.4, a range that affects the availability of both macro- and micro-nutrients. Therefore, major compositional shifts induced by pellet application must be accompanied by appropriate management of pH and C/N ratio to avoid nutrient lock-up or excessive nutrient leaching [18, 19].

Overall, these data imply that the application of pellet media with varying ratios (25:75, 50:50, 75:25) significantly alters the chemical profile of the planting media compared with the NPK control. With increases in macro-nutrients (N, P, K, Ca, Mg), greater organic matter content, and shifts in parameters such as C/N ratio and pH, pellet media have strong potential to improve soil fertility and nutrient supply for plants. However, such substantial changes also highlight the need for monitoring and balance, as nutrient imbalances, pH shifts, or suboptimal C/N ratios may affect plant performance or even induce stress.

3.2. Physical Properties. Figure 3 presents three key physical parameters of the planting media, porosity (%), permeability (cm/hour), and water retention (hours) across the four treatments: Control A (NPK), Treatment B (25:75), Treatment C (50:50), and Treatment D (75:25). In terms of porosity, Treatments C and D exhibited substantially higher values (56% and 54%, respectively) compared with the control (34%) and Treatment B (55%). This indicates that media mixtures containing non-NPK pellet components can increase pore spaces within the soil structure. The permeability parameter, which reflects the rate of water flow through the media, showed that the control (A) had the highest value (50 cm/hour). In contrast, Treatments B and C exhibited much lower values (20 cm/hour), with Treatment D slightly higher (21–22 cm/hour). This marked reduction in permeability in the mixed-pellet treatments suggests that the media become more resistant to rapid water flow or exhibit greater hydraulic impedance. Such conditions imply that pellets tend to slow the movement of free water and increase the duration of contact between water and the media, which in turn may enhance water retention and root accessibility.

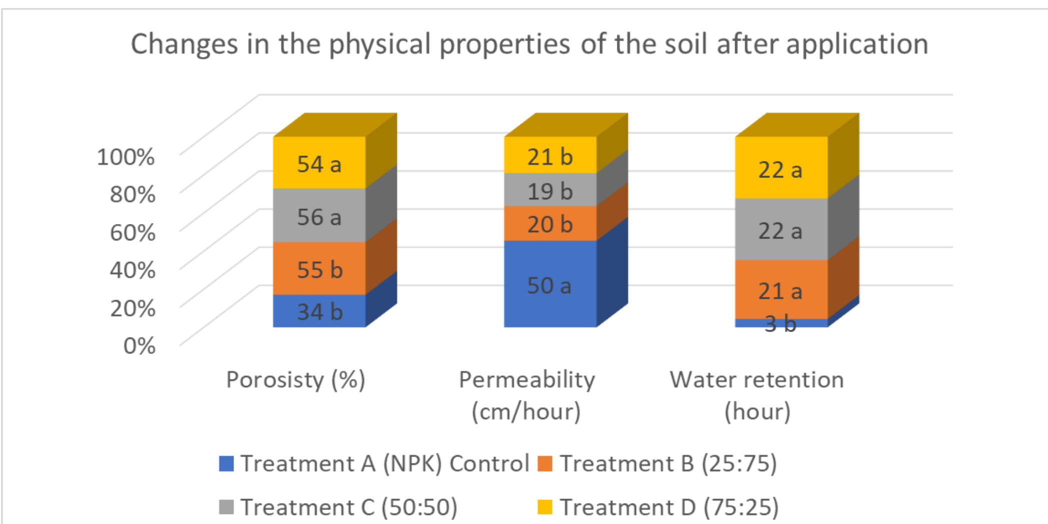

FIGURE 3. Changes in the physical properties of the soil after pellet application across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25), including porosity, permeability, and water retention.

For water retention, Treatment D had the highest value (22 hours), followed by Treatment C (22 hours) and Treatment B (21 hours), while the control showed the lowest retention time (3 hours). This demonstrates that media with higher pellet content substantially improve the soil's ability to retain water for extended periods. Such enhancement is critical for plant growth, as prolonged water availability in the root zone can reduce drought stress and improve plant performance. The relationship between increased organic matter and enhanced water-holding capacity is well documented, with literature noting that even a 1% increase in organic matter can significantly improve the amount of plant-available water in the soil [20].

3.3. Biological Properties. Figure 4 shows that treatments incorporating pellet-based planting media (Treatments B, C, and D) resulted in substantially higher counts of microbial colonies (fungi and bacteria) and greater symbiotic activity between earthworms and microorganisms than the control (Treatment A). The data indicate that total fungal colonies in the control reached only 28.7, whereas the pellet-based treatments ranged from 137.9 to 145.3. A similar pattern was observed for total bacterial colonies, with the control showing only 23.3, compared with 140-150 in the pellet treatments. These results indicate that richer planting media or mixtures containing organic components and microbial inoculants can significantly increase the abundance of both fungal and bacterial communities.

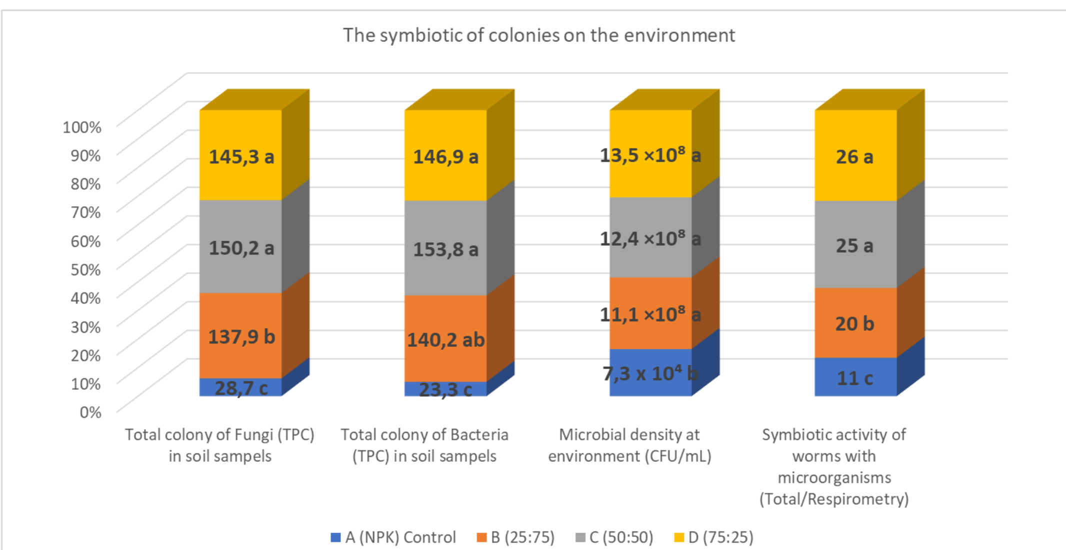

FIGURE 4. Biological responses of the soil environment following pellet application across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25), including total fungal colonies, total bacterial colonies, microbial density in the surrounding environment, and the symbiotic activity of earthworms with microorganisms.

Furthermore, environmental microbial density in the control was very low (7.3×10^4) compared with the mixed treatments, which ranged from 11.1×10^8 to 13.5×10^8. This demonstrates that not only the microbial colonies within the media increased, but also the activity and spatial distribution of microorganisms in the surrounding environment expanded substantially following pellet application. In addition, symbiotic interactions between earthworms and microorganisms increased from 11 in the control to 20–26 in the pellet treatments. This indicates that the combination of pellet-based planting media enhances positive interactions between soil fauna (earthworms) and microbial communities, thereby strengthening biological processes within the planting-medium ecosystem [21, 22].

From the perspective of planting-medium ecosystem functioning, these results reinforce the understanding that the presence and activity of microorganisms and soil fauna, such as earthworms, serve as important indicators of soil health and overall ecosystem functionality. Recent literature also shows that earthworm activity can alter microbial communities, soil structure, and nutrient processes (e.g., nitrogen mineralization) through mechanisms involving the drilosphere, the soil domain shaped by earthworm movement that becomes a specialized zone for microbial colonization.

3.4. Nutrient Release Kinetics (Gompertz Model). The dynamics of nutrient release from the pellet fertilizers were analyzed using the Gompertz model, which characterizes controlled-release behavior through three distinct phases: an initial lag phase, a subsequent exponential release phase, and a final plateau. This modeling approach provides a quantitative framework for understanding how the structural composition of the pellets, particularly the balance between organic and inorganic components, governs the temporal availability of key nutrients in the soil.

3.4.1. *Nitrogen Release*. Figure 5 illustrates the nitrogen (N) release curve modeled using the Gompertz function, highlighting the characteristic lag, exponential, and plateau phases. The nitrogen (N) release pattern from the pellet fertilizers exhibited a good fit with the Gompertz model, which characterizes gradual mineralization processes across three primary phases. During weeks 2 to 4, the system entered a lag phase with minimal N release due to the dominance of complex organic compounds (proteins and amides) that had not yet decomposed. The exponential phase occurred between weeks 6 and 10, marked by accelerated nitrogen release driven by the activity of decomposer microorganisms such as Azotobacter, Bacillus, and Actinomycetes, which convert organic nitrogen into inorganic forms (NH_4^+ and NO_3^-). After week 10, the system transitioned into a stable plateau phase, indicating a reduction in readily decomposable substrates and increasing nitrogen binding to humic complexes [7].

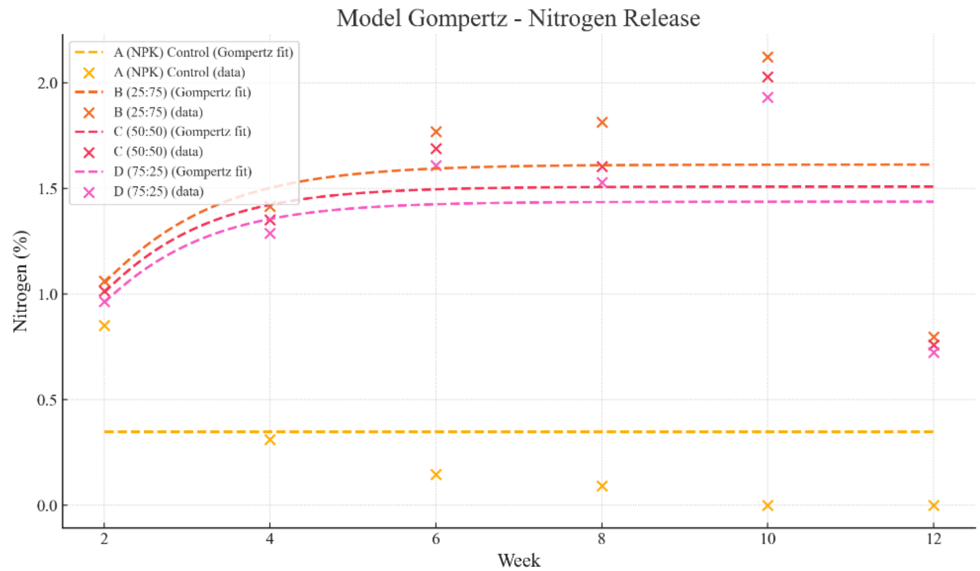

FIGURE 5. Gompertz model of nitrogen release following pellet application across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25).

Treatment B (25:75) and Treatment C (50:50) showed the highest release rates, reaching their peaks around week 10 with maximum N values exceeding 2%. This demonstrates that balanced proportions of organic and inorganic materials enhance the efficiency of gradual nitrogen release. In contrast, Treatment D (75:25) exhibited a slower release rate due to its high organic fraction, which led to nitrogen immobilization by soil microorganisms.

3.4.2. *Phosphate Release*. Figure 6 presents the phosphate (P) release profile following a Gompertz-type response across the pellet treatments. The phosphate (P) release pattern followed a sigmoid Gompertz curve, reflecting the dynamics of phosphorus mineralization from the pellet fertilizer. In the early phase (weeks 2 to 4), P release remained slow due to the dominance of organic phosphate forms and their association with metal complexes such as Fe, Al, and Ca in the soil. The acceleration phase occurred between weeks 6 and 10, marked by increasing activity of phosphate-solubilizing microorganisms, particularly *Bacillus* and *Pseudomonas* spp. which convert unavailable forms (Fe-P and Al-P) into soluble orthophosphate. After week 10, the system reached a stable plateau, as most of the available P had been solubilized or re-complexed onto soil colloids [1, 23].

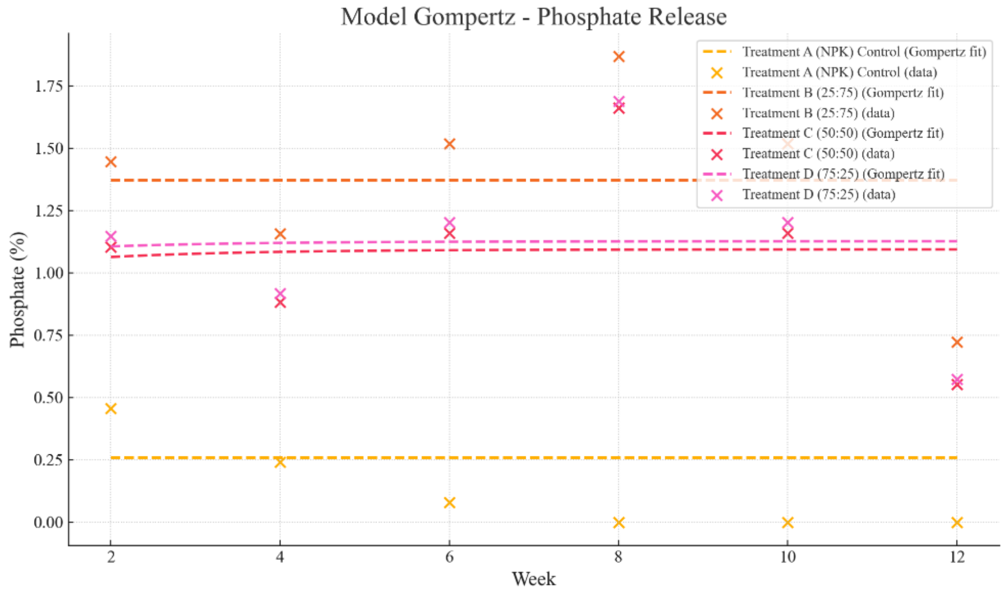

FIGURE 6. Gompertz model of phosphate release following pellet application across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25).

Treatment B (25:75) exhibited the highest release rate, reaching a peak of approximately ±1.8% at week 8, followed by Treatment C (50:50) and Treatment D (75:25). The combination of organic and inorganic components resulted in a slow-release mechanism that maintains P availability longer than the NPK control. Within the pellet structure, the organic matrix plays an important role as a binding agent (binder) that partially slows the dissolution of inorganic P, thereby supporting a gradual release aligned with the plant's nutrient requirements.

3.4.3. *Potassium Release*. Figure 7 presents the potassium (K) release kinetics modeled using the Gompertz curve, indicating gradual dissolution behavior. The potassium (K) release kinetics from the pellet fertilizers followed the Gompertz model, which represents the gradual dissolution dynamics of K^+ ions. Between weeks 2 and 6, a rapid increase in K release occurred due to the high solubility of potassium in the forms of K_2O and KCl, which readily dissociate from the pellet matrix. After week 8, the release rate slowed as the diffusion of K^+ ions became restricted by the porosity of the organic materials and the structural density of the pellet [19].

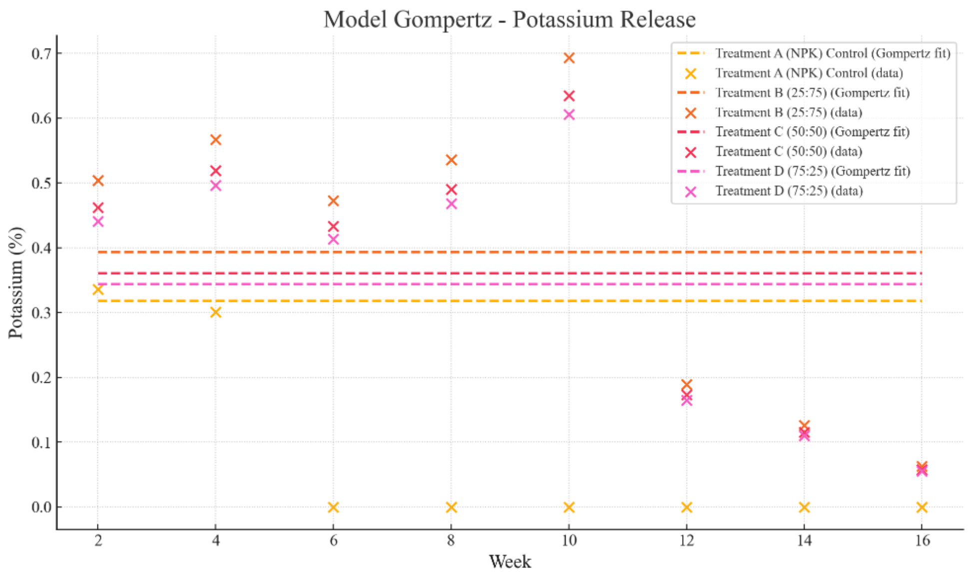

FIGURE 7. Gompertz model of potassium release following pellet application across four treatments (A: NPK control, B: 25:75, C: 50:50, D: 75:25)

Treatment B (25:75) exhibited the highest release rate, reaching a peak of 0.69%, compared with Treatments C (50:50) and D (75:25). This indicates that a lower proportion of organic material provides greater diffusion space, thereby increasing the mobility of K^+ ions into the soil solution. Conversely, a higher organic fraction results in stronger physical interactions between K^+ and the carboxyl and phenolic functional groups present in the organic matrix, consequently reducing the rate of K release.

4. Discussion

4.1. Physical, Chemical, and Biological Improvements. This study demonstrates that the application of pellet-based planting media, both organic and inorganic in varying ratios, produced integrated improvements in the physical, chemical, and biological properties of marginal soils. These outcomes align with the initial hypothesis that pelletization can function as a media-engineering strategy to enhance soil ecosystem services. The observations showed significant increases in porosity, water retention, and aggregate stability, accompanied by increases in macronutrient levels and microbial activity. These findings are consistent with previous reports on the potential of topsoil or soil pellets and organic amendments as rehabilitation strategies for degraded lands [7].

4.2. Physical, Chemical, and Biological Improvements. From a physical perspective, the improvements in porosity and water retention observed in the pellet-based treatments likely resulted from two interacting mechanisms: (i) the addition of structured organic fractions (such as rice-husk biochar and peanut shells), which enhance the media's capacity to adsorb and hold water; and (ii) modifications to particle structure and pore-size distribution facilitated by pellet aggregation. These effects align with literature showing that organic matter and biochar additions can increase water-holding capacity and improve micro–macropore structure, thereby reducing rapid water fluxes, an effect particularly important in sandy Entisols where increased contact time between water and root zones is beneficial [24].

Chemically, the increases in organic carbon, N, P, K, Ca, and Mg observed across mixed-pellet treatments indicate that pellets function both as reservoirs of bound nutrients and as gradual-release sources. However, variations in C/N ratios and pH across treatments show that nutrient availability is influenced not only by quantitative presence but also by microbial transformation processes (mineralization/immobilization) and sorption interactions with organic fractions. High C/N ratios can lead to temporary N immobilization, while shifts in pH may influence P availability and micronutrient behavior. These findings align with studies on biochar and slow-release fertilizers that highlight the influence of organic/mineral matrices on nutrient release and retention [25].

Enhanced microbial colony counts and macro-faunal activity (e.g., earthworms) in pellet treatments indicate that pellets provide substrates and microhabitats conducive to microbial proliferation and beneficial fauna–microbe interactions. Recent literature on microbial inoculants and bio-inocula supports the idea that biological amendments (including phosphate solubilizers, nitrogen fixers, and cellulose degraders) can accelerate the transformation of organic matter into soluble nutrients and enrich microbial diversity, especially critical in marginal soils. Successful local colonization by pellet-associated microbes is thus a key mechanism underlying the improved ecosystem functions observed in this study [26].

Potassium behavior, characterized by rapid initial release in higher-mineral-fraction treatments and slower release in high-organic-fraction treatments is consistent with literature indicating that readily soluble K fractions in biochar and mineral matrices become immediately available, whereas interactions with carboxyl and phenolic groups in organic matter delay K release. This is particularly important in sandy soils where K management is highly sensitive to leaching losses, making the organic–inorganic pellet ratio a crucial determinant of usable K availability [27].

4.3. Nutrient-Release Dynamics (Gompertz Model Interpretation). Nutrient-release kinetics modeled using the Gompertz function for N, P, and K showed strong conformity with the characteristic sequence of lag, exponential, and plateau phases typical of nutrient release from organic and composite amendments. Interpreting these phases provides practical insights: the lag phase corresponds to slow initial release due to complex organic compounds; the exponential phase reflects enhanced microbial activity and physical dissolution; and the plateau indicates the depletion of readily soluble substrates. The use of the Gompertz model is well supported in the literature for organic-release systems and allows for the estimation of parameters useful for designing fertilization schedules aligned with plant nutrient demands [28].

4.4. Agronomic Implications and Limitations. The agronomic implications for marginal sandy soils, such as the warm coastal Entisols used in this study suggest that pellets may serve as a multifunctional strategy capable of improving physical properties (through increased water retention), enhancing organic matter stocks, and providing a more stable nutrient supply compared with conventional liquid or soluble NPK inputs. Similar restoration and amendment studies reported improvements in planting frameworks and fertilizer-use efficiency under field conditions. However, long-term agronomic benefits require validation through crop-yield measurements, nutrient-use efficiency (NUE) assessments, and economic evaluations [7].

From a pellet-production standpoint, formulation visibility, including raw material type, particle size, pelletizing pressure, pre-heating/sterilization, and inoculum addition was shown to influence pellet properties and release behavior. The production processes used in this study, grinding, low-temperature drying, short parametric composting, and microbial inoculation via sprayer reflect best practices for maintaining microbial viability while reducing pathogens, although these parameters will need adjustment for large-scale production to ensure homogeneity and microbiological safety. Potential risks such as nutrient imbalance, undesirable pH shifts, or contaminants must also be evaluated before wide-scale adoption.

Overall, this study provides empirical evidence that transforming planting media into pellets, when properly formulated, represents a promising integrated approach for improving marginal soil quality through enhanced physical properties, controlled nutrient release, and stimulation of soil biological communities. For practical adoption and policymaking, key recommendations include optimizing organic–inorganic pellet ratios for specific objectives, standardizing production protocols for microbial safety, conducting multi-season field trials, and integrating agronomic monitoring with environmental assessments to ensure long-term benefits. These results open opportunities for incorporating bio-pellets into sustainable land rehabilitation strategies [12, 29–31].

5. Conclusion

This study demonstrates that pellet-based planting media, both organic and inorganic, can effectively improve the physical, chemical, and biological quality of marginal sandy soils. Increases in porosity, water retention, and aggregate stability highlight the effectiveness of pellet structural engineering in optimizing soil aeration and moisture conditions that are essential for root development. Chemically, the increases in organic carbon and macronutrient availability (N, P, K, Ca, Mg) confirm that pellets function both as nutrient sources and soil conditioners with controlled nutrient-release patterns. The Gompertz modeling results further reveal a gradual release mechanism that maintains nutrient availability while reducing losses through leaching. From a biological perspective, enhanced microbial colonization and soil-fauna activity strengthen soil ecosystem functions through mineralization processes and aggregate formation. These outcomes indicate that pellets contribute to restoring soil biotic activity, which is crucial for natural fertility and agroecosystem sustainability. Overall, transforming planting media into pellet form represents a promising agronomic innovation for improving soil fertility in a sustainable manner. This approach merits further development at field and economic scales to support marginal-land rehabilitation and regenerative agriculture in tropical regions.

Acknowledgment

The authors extend heartfelt gratitude to the Directorate of Research, Technology, and Community Service; the Directorate General of Higher Education, Research, and Technology; and the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for providing funding for this research under the Fundamental Research scheme in 2025 (Contract No. 126/C3/DT.05.00/PL/2025 and 0498.28/LL5-INT/AL.04/2025).

Author Contributions

Dian Pratama Putra: Conceptualization, Methodology, Writing – Original Draft, Formal analysis. Nanda Satya Nugraha: Methodology, Formal analysis, Investigation. Mohammad Prasanto Bimantio: Methodology, Formal analysis, Investigation. Teddy Suparyanto: Formal analysis, Investigation. Kuncahyo Setyo Nugroho: Software, Writing – Review & Editing. Bens Pardamean: Validation, Supervision.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

REFERENCES

[1] D.P. Putra, M.P. Bimantio, A.A. Sahfitra, T. Suparyanto, B. Pardamean, Simulation of Availability and Loss of Nutrient Elements in Land with Android-Based Fertilizing Applications, in: 2020 International Conference on Information Management and Technology (ICIMTech), IEEE, 2020, pp. 312-317. https://doi.org/10.1109/ICIMTech50083.2020.9211268.

[2] J. Baurley, A. Perbangsa, A. Subagyo, B. Pardamean, A Web Application and Database for Agriculture Genetic Diversity and Association Studies, Int. J. Biosci. Biotechnol. 5 (2013), 33-42. https://doi.org/10.14257/ijbsbt.2013.5.6.04.

[3] T.W. Cenggoro, A. Budiarto, R. Rahutomo, B. Pardamean, Information System Design for Deep Learning Based Plant Counting Automation, in: 2018 Indonesian Association for Pattern Recognition International Conference (INAPR), IEEE, 2018, pp. 329-332. https://doi.org/10.1109/INAPR.2018.8627019.

[4] H. Herman, T.W. Cenggoro, A. Susanto, B. Pardamean, Deep Learning for Oil Palm Fruit Ripeness Classification with DenseNet, in: 2021 International Conference on Information Management and Technology (ICIMTech), IEEE, 2021, pp. 116-119. https://doi.org/10.1109/ICIMTech53080.2021.9534988.

[5] H. Soeparno, A.S. Perbangsa, B. Pardamean, Best Practices of Agricultural Information System in the Context of Knowledge and Innovation, in: 2018 International Conference on Information Management and Technology (ICIMTech), IEEE, 2018, pp. 489-494. https://doi.org/10.1109/ICIMTech.2018.8528187.

[6] D. Liang, Y. Wang, H. Shi, Z. Luo, R.L. Quirino, et al., Controllable Release Fertilizer with Low Coating Content Enabled by Superhydrophobic Castor Oil-Based Polyurethane Nanocomposites Prepared Through a One-Step Synthetic Strategy, Ind. Crop. Prod. 189 (2022), 115803. https://doi.org/10.1016/j.indcrop.2022.115803.

[7] T.P. Munro, T.E. Erickson, D.G. Nimmo, F.A. Dadzie, M. Muñoz-Rojas, et al., Exploring the Potential of Topsoil Pellets to Improve Native Seedling Establishment on Degraded Agricultural Land, Plant Soil 502 (2024), 417–432. https://doi.org/10.1007/s11104-024-06554-5.

[8] P.O. Adomi, O.L. Oyubu, Formulation and Cultivation of Microorganism Using Alternative Media From Agricultural Wastes, J. Adv. Microbiol. Res. 4 (2023), 26-31.

[9] S. Zhang, M. Yang, S. Meng, Y. Yang, Y.C. Li, et al., Biowaste-Derived, Nanohybrid-Reinforced Double-Function Slow-Release Fertilizer with Metal-Adsorptive Function, Chem. Eng. J. 450 (2022), 138084. https://doi.org/10.1016/j.cej.2022.138084.

[10] D.P. Putra, N.S. Nugraha, M.P. Bimantio, et al. Biological Planting Media as Marginal Land Resolution with Local Bio Introduction, Commun. Math. Biol. Neurosci. 2024 (2024), 125. https://doi.org/10.28919/cmbn/8913.

[11] Z. Guo, W. Qiang, J. He, X. Han, X. Tan, et al., Nitrogen Deposition Raises Temperature Sensitivity of Soil Organic Matter Decomposition in Subtropical Forest, Sci. Total. Environ. 907 (2024), 167925. https://doi.org/10.1016/j.scitotenv.2023.167925.

[12] T. Bachtiar, A.R. Syahputra, A. Citraresmini, R. Nurjayati, H. Hidawati, et al., Performances of Phosphate-Solubilizing Microorganisms on Soil Chemical Properties Under Different Soil Characteristics: A Meta-Analysis, J. Degraded Min. Lands Manag. 11 (2024), 6351-6366. https://doi.org/10.15243/jdmlm.2024.114.6351.

[13] M.H. Samsudin, M.Z.M. Yusoff, M.A. Hassan, M.R. Zakaria, A.M. Roslan, et al., Assessment of Pilot-Scale Sewage Sludge Pelletization for Non-Food Crop Fertilization: Nutrient Content, Pathogenicity, and Growth Performance, Environ. Monit. Assess. 196 (2024), 807. https://doi.org/10.1007/s10661-024-12956-w.

[14] X. Ma, S. Zhang, Y. Yang, Z. Tong, T. Shen, et al., Development of Multifunctional Copper Alginate and Bio-Polyurethane Bilayer Coated Fertilizer: Controlled-Release, Selenium Supply and Antifungal, Int. J. Biol. Macromol. 224 (2023), 256-265. https://doi.org/10.1016/j.ijbiomac.2022.10.121.

[15] A.P. Dovzhenko, O.A. Yapryntseva, K.O. Sinyashin, T. Doolotkeldieva, R.R. Zairov, Recent Progress in the Development of Encapsulated Fertilizers for Time-Controlled Release, Heliyon 10 (2024), e34895. https://doi.org/10.1016/j.heliyon.2024.e34895.

[16] R.E. Caraka, M. Tahmid, R.M. Putra, A. Iskandar, M.A. Mauludin, et al., Analysis of Plant Pattern Using Water Balance and Cimogram Based on Oldeman Climate Type, IOP Conf. Ser.: Earth Environ. Sci. 195 (2018), 012001. https://doi.org/10.1088/1755-1315/195/1/012001.

[17] A. Arma, L. Alrayes, T.H. Pham, M. Nadeem, C. Manful, et al., Rock Dust-Based Potting Media Enhances Agronomic Performance and Nutritional Quality of Horticultural Crops, Curr. Plant Biol. 40 (2024), 100419. https://doi.org/10.1016/j.cpb.2024.100419.

[18] O.J. Rotowa, S. Małek, D. Kupka, M. Pach, J. Banach, Innovative Peat-Free Organic Substrates and Fertilizers Influence Growth Dynamics and Root Morphology of Fagus Sylvatica L. and Quercus Robur L. Seedlings One Year After Planting, Forests 16 (2025), 800. https://doi.org/10.3390/f16050800.

[19] T. Alam, M. Ikram, A.N. Chaudhry, C.M. Subhan, K.D. Alotaibi, et al., Utilization of Organic-Residues as Potting Media: Physico-Chemical Characteristics and Their Influence on Vegetable Production, PLOS ONE 19 (2024), e0302135. https://doi.org/10.1371/journal.pone.0302135.

[20] C.A. Clark, The Important Role of Soil Texture on Water, https://cropsandsoils.extension.wisc.edu/articles/the-important-role-of-soil-texture-on-water.

[21] R.M. Medina-Sauza, M. Álvarez-Jiménez, A. Delhal, F. Reverchon, M. Blouin, et al., Earthworms Building up Soil Microbiota, a Review, Front. Environ. Sci. 7 (2019), 81. https://doi.org/10.3389/fenvs.2019.00081.

[22] Q. Chen, Y. Song, Y. An, Y. Lu, G. Zhong, Soil Microorganisms: Their Role in Enhancing Crop Nutrition and Health, Diversity 16 (2024), 734. https://doi.org/10.3390/d16120734.

[23] M.T. Hafizal, D.P. Putra, H. Wirianata, N.S. Nugraha, T. Suparyanto, et al., Implementation of Expert Systems in Potassium Deficiency in Cocoa Plants Using Forward Chaining Method, Procedia Comput. Sci. 216 (2023), 136-143. https://doi.org/10.1016/j.procs.2022.12.120.

[24] L. Xu, K. Wu, Z. Deng, C. Huang, K.K. Verma, et al., Biochar and Its Impact on Soil Profile and Plant

Development, J. Plant Interactions 19 (2024), 2401356. https://doi.org/10.1080/17429145.2024.2401356.

[25] M. Chen, J. Han, P. Shi, J. Wang, Y. Wang, et al., Preparation of Biochar Slow-Release Phosphate Fertilizer Granules with Starch-Cmc-Na Binder: Improving Granule Mechanical and Slow-Release Properties, J. Environ. Chem. Eng. 13 (2025), 119547. https://doi.org/10.1016/j.jece.2025.119547.

[26] A.M. Díaz-Rodríguez, F.I. Parra Cota, L.A. Cira Chávez, L.F. García Ortega, M.I. Estrada Alvarado, et al., Microbial Inoculants in Sustainable Agriculture: Advancements, Challenges, and Future Directions, Plants 14 (2025), 191. https://doi.org/10.3390/plants14020191.

[27] L. Xiu, W. Gu, Y. Sun, D. Wu, Y. Wang, et al., The Fate and Supply Capacity of Potassium in Biochar Used in Agriculture, Sci. Total. Environ. 902 (2023), 165969. https://doi.org/10.1016/j.scitotenv.2023.165969.

[28] D. Lohr, N.S. Gruda, E. Meinken, Estimating Nitrogen Release from Organic Fertilizers for Soilless Production by Analysis of C and N Pools, Horticulturae 9 (2023), 767. https://doi.org/10.3390/horticulturae9070767.

[29] N.F. Amir, A. Mohd-Aris, T.N. Tuan-Zakaria, N.A. Umor, A. Mohamad, et al., Effect of Physiochemical Parameters on Yield and Biological Efficiency of Volvariella Volvacea Cultivated on Empty Fruit Bunch Pellets, Heliyon 11 (2025), e42572. https://doi.org/10.1016/j.heliyon.2025.e42572.

[30] E. Firmansyah, B. Pardamean, C. Ginting, H.G. Mawandha, D. Pratama Putra, et al., Development of Artificial Intelligence for Variable Rate Application Based Oil Palm Fertilization Recommendation System, in: 2021 International Conference on Information Management and Technology (ICIMTech), IEEE, 2021, pp. 6-11. https://doi.org/10.1109/ICIMTech53080.2021.9535082.

[31] T. Sung-inthara, S. Juntahum, K. Senawong, S. Katekaew, K. Laloon, Pelletization of Soil Amendment: Optimizing the Production and Quality of Soil Amendment Pellets from Compost with Water and Biochar Mixtures and Their Impact on Soil Properties, Environ. Technol. Innov. 33 (2024), 103505. https://doi.org/10.1016/j.eti.2023.103505.