Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx **DOI:** https://doi.org/xx

VALORIZATION OF PALM KERNEL SHELL BIOCHAR AND BOILER ASH INTO SOLID ORGANIC FERTILIZER: DEVELOPMENT AND QUALITY EVALUATION

Nova Tri Buyana[1*], Yuliantina Azka[1], Gempur Irawan Supena Putra[2], Syahidah Asma Amanina[3], Muharnawan Jumadi[4]

[1]Department of Agrotechnology, Faculty of Agriculture, Tridinanti University, Palembang 30129, South Sumatra, Indonesia.

[2]Department of Biochemistry, Faculty of Mathematics and Natural Sciences, IPB University, Bogor 16680, West Java, Indonesia.

[3]Faculty of Pharmacy Universitas Indonesia, Depok 16424, West Java, Indonesia.

[4]Research and Development Division of PT. Agrinas Palma Nusantara (Persero), Jakarta 13340, Indonesia.

*nova@univ-tridinanti.ac.id

Abstract: Palm oil processing generates substantial solid waste that remains underutilized despite its significant potential as a renewable biomass resource. Among these residues, palm kernel shells and boiler ash are particularly promising due to their complementary nutrient profiles, with high organic carbon (C) and potassium (K) contents, respectively. This study aims to develop and evaluate a solid organic fertilizer derived from these materials and to assess its chemical quality in accordance with SNI 7763:2024 standards. The research involved optimization of three fertilizer formulations using different proportions of palm kernel shell biochar and boiler ash, followed by comprehensive chemical and nutrient analyses. The results demonstrate that the optimal formulation yields a nutrient-enriched fertilizer containing nitrogen (N) 0.82%, phosphorus (P) 4.355%, potassium (K_2O) 3.97%, magnesium (MgO) 3.44%, organic carbon (C) 15.41%, iron (Fe) 7283.8 ppm, and zinc (Zn) 589 ppm. All parameters meet the quality requirements specified in SNI 7763:2024, indicating the product's suitability as a solid organic fertilizer. These findings highlight the potential of palm oil biomass waste as a value-added resource for sustainable fertilizer production, contributing to circular agro-industrial development, waste valorization, and environmental sustainability.

Keywords: *Biochar; Boiler Ash; Palm Kernel Shell; Slow-Release Fertilizer*.

(Received 2026-05-19, Accepted 2026-05-25, Available Online by 2026-05-31)

1. Introduction

The oil palm industry generates substantial volumes of biomass residues. In Indonesia alone, biomass waste production from the oil palm sector reached 22 million tons in 2021 (Nabila *et al.*, 2023). From every ton of fresh fruit bunches (FFB), approximately 22–23% (220–230 kg) becomes empty fruit bunches, while other wastes include palm kernel shells (6.5% or 65 kg), palm sludge (4% or 40 kg), fiber

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx DOI: https://doi.org/xx

(13% or 130 kg), and liquid waste (50%) (Mandiri, 2012). Among these residues, palm kernel shell (PKS) and palm oil boiler ash (POBA) hold strong potential for further valorisation.

FFB typically produce 6–7% PKS as by-products (Abdulrazik *et al.*, 2017), while boiler ash production in Indonesia is estimated at 1.1 million tons annually (Nabila *et al.*, 2023). PKS is chemically dominated by carbon (48.06–57.91%), oxygen (34.10–49.99%), and smaller proportions of hydrogen, nitrogen, and sulfur (Abnisa *et al.*, 2013; Idris *et al.*, 2012). Meanwhile, POBA contains a high proportion of SiO_2 (68.13%), along with K_2O (7.88%), CaO (7.25%), P_2O_5 (7.34%), MgO (2.90%), and trace minerals (Jonbi *et al.*, 2025). These nutrient-rich characteristics indicate that PKS-derived biochar and POBA have strong potential as sources of both macro- and micronutrients for plant growth. The utilisation of biochar in fertilizer formulations has demonstrated positive effects on soil fertility and nutrient retention (Das *et al.*, 2021). Biochar-enhanced fertilizers, for instance, have been shown to increase nitrogen use efficiency by up to 20% and improve crop yields by over 10% (Jia *et al.*, 2021). They can also reduce nitrogen leaching by 11–13%, thereby minimising nutrient losses and mitigating environmental impacts (Alkharabsheh *et al.*, 2021). Previous studies have predominantly investigated the separate utilization of palm kernel shell biochar and palm oil boiler ash as soil amendments or organic fertilizer components. However, studies evaluating their synergistic integration within a single solid organic fertilizer formulation, particularly in relation to formulation optimization, nutrient quality, and compliance with SNI standards, remain very limited.

Globally, the development of solid organic fertilizers has gained significant attention due to increasing concerns over the excessive use of chemical fertilizers, which contribute to soil degradation, water pollution, and greenhouse gas emissions (Deng et al., 2024; Gu et al., 2023). Solid organic fertilizers derived from agricultural biomass are considered a sustainable alternative because they improve soil fertility, enhance soil physical properties, and support environmentally friendly agricultural practices. Palm kernel shell (PKS) biochar is recognized for its high carbon content, porous structure, and ability to improve soil moisture retention and microbial activity (Jiang et al., 2025). In addition, palm oil boiler ash (POBA) contains essential mineral nutrients such as potassium, calcium, and magnesium that can support plant growth and soil nutrient availability. Previous studies have mainly focused on the separate utilization of PKS biochar or POBA as soil amendments or fertilizer components. However, studies evaluating their combined application in a single solid organic fertilizer formulation remain limited, particularly in relation to formulation optimization, nutrient characteristics, and compliance with fertilizer quality standards. Therefore, this study combined palm kernel shell biochar and boiler ash to formulate a solid organic fertilizer and evaluate its chemical quality based on SNI 7763:2024 standards, as well as its potential as a sustainable nutrient source for agricultural applications.

2. Research Methods

2.1 Materials

The materials used in this study were palm kernel shells obtained from an oil palm plantation in South Sumatra. Meanwhile, palm oil boiler ash was obtained from a palm oil processing plant (PKS) in South Sumatra. Other fertilizer ingredients included molasses, bentonite clay, humic acid, and standard analytical chemicals such as HCl and NaOH solutions, along with indicators used in fertilizer quality testing in accordance with SNI 7763:2024 standards for Solid Organic Fertilizer. The instruments used in this study were Memmert UN 55 oven, crusher, sieve shaker, sieve, simple pyrolysis reactor, pellet mold, bench scale, kjeldahl therm, kjeldahl flask, 10 mL measuring cylinder, 100 mL measuring cylinder, watch glass, electric heater, Ohaus Pioneer PX22 analytical balance, Mettler Toledo pH meter, and Agilent cary 60-UV-Vis spectrophotometer, glass container, closed plastic container for sample storage, laboratory

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx **DOI:** https://doi.org/xx

glassware such as measuring cylinder, pipette, and Erlenmeyer flask used in the chemical analysis process.

2.2 Methods

2.2.1 Palm Kernel Shell Preparation

Palm kernel shells are first cleaned of dirt and then dried in an oven at 110°C for 1.5 hours to remove moisture. After drying, the kernel shells are crushed using a crusher to achieve a smaller, more uniform size. Next, they are sieved using a sieve shaker to obtain particles with a diameter of 300–600 μm. The palm kernel shell pyrolysis process is carried out using a simple pyrolysis reactor with a capacity of 20 kg to produce biochar. The resulting biochar is then cooled to room temperature before being used in fertilizer formulation.

2.2.2 Solid Organic Fertilizer Formulation

The solid organic fertilizer was formulated using palm kernel shell biochar and palm oil boiler ash as the primary materials, with the formulation composition presented in Table 1. In addition to the main materials, bentonite (30% w/w) was used as a binder and filler material, while molasses solution (5% w/v) and humic acid solution (10% w/v) were added as supplementary additives during the mixing process. All components were thoroughly mixed until a homogeneous mixture was obtained. The mixture was then molded into pellet forms and air-dried at room temperature for 3–5 days to reduce moisture content. After drying, the solid organic fertilizer pellets were stored in sealed containers for further analysis.

Table 1. Solid organic fertilizer formulation

Formulation	Main Ingredients 70% (A)		Additive Ingredients 30% (B)
	Boiler Ash	Kernel Shell	Bentonite
F1	25% of A	75% of A	30% (A+B)
F2	50% of A	50% of A	30% (A+B)
F3	75% of A	25% of A	30% (A+B)

2.2.3 Solid Organic Fertilizer Quality Analysis

The quality testing of the solid organic fertilizer followed the procedures outlined in SNI 7763:2024 concerning the Minimum Technical Requirements for Solid Organic Fertilizers. The analyzed parameters included water content, organic carbon (%), C/N ratio, pH, macronutrients (N, P_2O_5, K_2O, and MgO), and micronutrients (total Fe and total Zn). The evaluation focused on determining the chemical quality and nutrient characteristics of the formulated solid organic fertilizer.

3. Result and Discussion

3.1 Solid Organic Fertilizer Quality Analysis

The differences in the composition of palm oil boiler ash among formulations P1, P2, and P3 significantly influenced the chemical characteristics of the resulting solid organic fertilizer. Boiler ash is known to contain various mineral elements, particularly potassium, calcium, magnesium, and silica, which contribute to changes in pH, ash content, nutrient concentration, and organic matter characteristics. In this study, increasing the proportion of boiler ash in the formulation tended to increase the ash content and alkalinity of the fertilizer due to the accumulation of inorganic mineral compounds. On the other hand, variations in the proportion of palm kernel shell biochar affected the organic carbon content and subsequently influenced the C/N ratio of each formulation.

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx DOI: https://doi.org/xx

Furthermore, the interaction between boiler ash and biochar components also affected nutrient retention and the overall stability of the fertilizer matrix. Formulations containing higher amounts of boiler ash generally showed improved mineral nutrient availability, while formulations dominated by biochar exhibited relatively higher carbon content. These findings demonstrate that the balance between boiler ash and biochar composition plays an important role in determining the physicochemical properties and quality of the solid organic fertilizer produced. Therefore, the observed variations among P1, P2, and P3 indicate that formulation composition is a key factor in optimizing fertilizer characteristics to meet quality standards and improve potential agricultural application performance.

Table 2. Quality of the organic solid fertilizer

No	Test Parameter	Unit	Method	Formulation			SNI 7763:2024 Standard
				P1 25% Boiler Ash	P2 50% Boiler Ash	P3 75% Boiler Ash	
1	Water content	%	Gravimetry	3,24	3,35	3,56	8-25
2	pH		Potensiomentry	5,18	5,87	6,34	4-9
3	C-Organic	%	Gravimetry	21,98	18,9	15,41	Min 15%
4	C/N			37,90	28,21	18,79	Max 25
5	Macronutrient						
	N Total	%	Titrimetry	0,58	0,67	0,82	N+P+K = min 2
	P_2O_5	%	Spectrofomentry	1,097	3,896	4,355	
	K_2O Total	%	AAS	1,67	3,16	3,97	
6	MgO Total	%	AAS	2,15	3,09	3,44	
7	Fe Total	ppm	AAS	7083,8	8183,8	7283,8	max 15000
8	Zn	ppm	AAS	458	569	589	max 5000

3.2 Discussion

3.2.1 Water content

The quality assessment of solid organic fertilizers includes the evaluation of physical and chemical parameters such as water content, pH, organic carbon (C-organic), C/N ratio, and macro- and micronutrient composition. Water content refers to the percentage of water present in a material relative to its wet or dry weight (Widarti *et al.*, 2015). As shown in Table 1, the water content of the fertilizer formulations varies, increasing with higher proportions of boiler ash. The water content values for formulations P1, P2, and P3 are 3.24%, 3.35%, and 3.56%, respectively. According to SNI 7763:2024, the acceptable water content for solid organic fertilizers is 8–25%. Water content plays a vital role in determining the shelf life of fertilizer products, as it influences the rate of chemical and biological changes. Higher water content accelerates the decomposition of organic materials, whereas low water content slows this process during storage. Once applied to soil, increasing soil moisture facilitates microbial activity and the dissolution of organic components within the fertilizer (Widarti *et al.*, 2015).

3.2.2 pH

The pH value of the organic solid fertilizers was analysed following the SNI 7763:2024 guidelines. The results show that pH increases proportionally with the concentration of boiler ash. The pH values for formulations P1, P2, and P3 are 5.18, 5.87, and 6.34, respectively, all of which meet the required pH range of 4–9. (Widarti *et al.*, 2015) note that the optimal pH for composting lies between 6.5 and 7.5. Throughout the composting process, organic matter undergoes biochemical transformation, resulting in changes in pH; mature compost typically approaches a neutral pH.

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx **DOI:** https://doi.org/xx

3.2.3. Organic matter content

Organic matter content is determined by measuring the amount of organic carbon present. Based on the analysis, the C-organic content of formulations P1, P2, and P3 is 21.98%, 18.9%, and 15.41%, respectively. These values comply with SNI 7763:2024, which requires a minimum of 15% organic carbon. Fertilizers with high C-organic content can enhance soil nutrient cycling and overall soil fertility (Li *et al.*, 2018).

3.2.3 C/N ratio

The C/N ratio also varied across formulations. Increasing the proportion of boiler ash resulted in a decrease in the C/N ratio. Formulation P3 met the SNI requirement with a C/N ratio of 18.79, while formulations P1 (37.90) and P2 (28.21) exceeded the maximum permitted value of 25. An appropriate C/N ratio is essential to ensure an efficient decomposition process in organic fertilizers. According to Pandebesie & Rayuanti (2013), decomposition is strongly influenced by the C/N ratio: excessively high ratios slow microbial activity, while very low ratios accelerate decomposition only at early stages before becoming limited by insufficient carbon for microbial energy supply.

3.2.4 Macronutrient content

The macronutrient content analysis in solid organic fertilizer was carried out by determining the percentage of macronutrients N, P_2O_5, K_2O, and MgO according to the procedures in SNI 7763:2024. Macronutrients are essential elements required by plants in large quantities because they play a role as the main components of plant tissue and determine soil productivity. The main macronutrients include nitrogen (N), phosphorus (P), and potassium (K), known as NPK elements (Agrahari *et al.*, 2021). Based on the test results, it can be seen that the nitrogen (N) content in the fertilizer was 0,58%; 0,67%; and 0,82% in P1, P2, and P3 formulation.

Nitrogen is a fundamental nutrient in plant nutrition, functioning as the main component of most fertilizers and often serving as the primary limiting factor for crop growth. It is essential for the biosynthesis of chlorophyll, amino acids, nucleic acids, and proteins, all of which drive vigorous vegetative development (Agrahari *et al.*, 2021). At the cellular level, nitrogen forms the core of purines and pyrimidines in DNA and RNA, and it constitutes the amine groups of amino acids that build peptides, proteins, and enzymes. In plant shoots, a substantial proportion of nitrogen is localized in chloroplasts, particularly in RuBisCo, photosystem proteins, and chlorophyll molecules, which contain four nitrogen atoms embedded in the chlorin (tetrapyrrole) ring. In addition, nitrogen-containing species such as nitrate (NO_3^-), ammonium (NH_4^+), and nitric oxide (NO) serve as crucial signaling molecules regulating plant metabolic and developmental processes (de Bang *et al.*, 2021).

The phosphorus content in the form of P_2O_5 in the fertilizer was 1,097%; 3,896%; and 4,355% in P1, P2, and P3 respectively. Phosphorus plays a central role in supporting root formation, energy transfer, photosynthesis, fruiting, and flowering (Dikr, 2022). Phosphorus is a structural element of key metabolites involved in energy transformations, including ATP and NADPH, and forms part of nucleic acids and membrane phospholipids. The hydrolysis of the P–O–P bond in ATP to generate ADP and inorganic phosphate (Pi) represents the primary biochemical energy source sustaining cellular metabolism (Kamerlin *et al.*, 2013). Plants generally absorb phosphorus in the form of inorganic orthophosphate ions such as $H_2PO_4^-$ or HPO_4^{2-} with the dominant species depending on soil pH conditions (de Bang *et al.*, 2021).

The potassium content in the form of K_2O in the fertilizer was 1,67%; 3,16%; and 3,97% in P1, P2, and P3, respectively. The total NPK content has qualified the SNI standard with the minimum percentage value of 2%. Potassium contributes significantly to plant reproductive processes, including fruiting and flowering (Dikr, 2022), while also playing diverse physiological roles such as osmotic regulation, enzyme

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx DOI: https://doi.org/xx

activation, and overall maintenance of plant health (Kumar *et al.*, 2024). Unlike nitrogen and phosphorus, potassium does not form covalent bonds; instead, its function is mediated entirely through the activity of the K^+ ion. K^+ is essential for maintaining cellular electro-neutrality, regulating osmotic balance, and stabilizing cytosolic pH, making it a cornerstone of intracellular homeostasis (de Bang *et al.*, 2021). Most K^+ is stored in vacuoles, where it generates turgor pressure and contributes to cell expansion. It also enhances the stability and activity of numerous enzymes—more than 70 reported cases—including key metabolic enzymes such as pyruvate kinase, phosphofructokinase, and starch synthase (Anschütz *et al.*, 2014).

Additionally, secondary macronutrients such as magnesium (Mg) are also important for plants. The magnesium (Mg) content in fertilizers is 2,15%; 3,09%; 3,44% in P1, P2, and P3 fertilizers, respectively. Magnesium (Mg) plays an indispensable role in plant metabolism, functioning as the central atom of the chlorophyll molecule and facilitating the transfer of energy and nutrients within plant tissues (Kirkby, 2023). As the core driver of photosynthesis, chlorophyll depends on adequate Mg availability for both its synthesis and functionality (Tang & Luan, 2020). When Mg is deficient, chlorophyll formation is impaired, reducing the plant's capacity to convert solar energy into chemical energy (Peng *et al.*, 2019). Structurally, Mg occupies the central position of the tetrapyrrole ring in chlorophyll, where it fine-tunes the molecule's electronic properties, thereby enhancing photon capture and the transfer of excitation energy from the light-harvesting complexes (LHCs) to the PSII reaction center (de Bang *et al.*, 2021). In addition to its covalent binding in chlorophyll, Mg also forms ionic complexes with negatively charged sites in the cell wall. The composition and cation exchange capacity of plant cell walls differ across species, resulting in characteristic stoichiometric relationships between Mg and Ca concentrations among various angiosperm groups (White *et al.*, 2018). Beyond structural roles, Mg's strong electropositive nature enables it to form ternary complexes with enzymes, stabilizing enzyme–substrate interactions and enhancing catalytic efficiency (de Bang *et al.*, 2021).

3.2.5 Micronutrient content

The micronutrient content analysis in solid organic fertilizer was carried out by determining the percentage of Zinc (Zn) and Iron (Fe) according to the procedures in SNI 7763:2024. Micronutrients are essential elements required by plants in minimal quantities for optimal growth, plant development, and reproduction. Micronutrient required in small amount but plays a vital role in various physiological and metabolic processes (Ahmed *et al.*, 2024).

The iron (Fe) content in fertilizers is 7083,8 ppm; 8183,8 ppm; and 7283,8 ppm in P1, P2, and P3 fertilizers, respectively. These result has qualified the SNI standard 7763:2024 standard, which is a maximum of 15000 ppm Fe content. Iron (Fe) is a pivotal micronutrient that supports numerous enzymatic reactions essential for plant survival. It is deeply integrated into processes such as photosynthesis, respiration, and nitrogen assimilation, making it a determinant of overall plant metabolic efficiency (Li *et al.*, 2021). When Fe concentrations decline, these systems become dysregulated, resulting in reduced vitality and impaired growth (Herlihy *et al.*, 2020). Fe is required not only for chlorophyll biosynthesis but also for the functioning of photosystems that mediate light energy conversion (Li *et al.*, 2021). Insufficient Fe disrupts these electron-transfer processes, leading to inefficient energy capture and subsequent growth reduction (Li *et al.*, 2021; Vélez-Bermúdez & Schmidt, 2023). Moreover, Fe also serves a signaling role, modulating physiological pathways related to nutrient uptake, transport, and homeostasis (Gao *et al.*, 2019; Herlihy *et al.*, 2020).

The zinc (Zn) content in fertilizers is 458 ppm; 569 ppm; 589 ppm in P1, P2, and P3 fertilizers, respectively. These result has qualified the SNI standard 7763:2024 standard, which is a maximum of 5000 ppm Fe content. Zinc (Zn) is equally vital for plant development, particularly in sustaining a robust root system and improving tolerance to biotic and abiotic stresses (Kabiri *et al.*, 2017). At the cellular level, Zn contributes to a broad range of biochemical pathways, including DNA synthesis and carbohydrate metabolism, underscoring its centrality to plant growth (Balandrán-Valladares *et al.*, 2021). Zn also plays a regulatory role in hormone biosynthesis, particularly auxins, which govern cell elongation, root branching, and the initiation of flowering (Balafrej *et al.*, 2020; Otiende *et al.*, 2021; Tripathi *et al.*, 2022). Disruption of Zn availability can therefore lead to significant developmental imbalances, affecting plant vigor and reproductive success (Suganya *et al.*, 2020). Furthermore, Zn is crucial for tryptophan synthesis, a precursor for auxin formation, thereby influencing seed viability and overall reproductive capacity (Otiende *et al.*, 2021; Suganya *et al.*, 2020; Tripathi *et al.*, 2022).

4. Conclusion

The formulation study of solid organic fertilizer identified Formulation 3 as optimal, consisting of 75% boiler ash and 25% palm kernel shell biochar as the primary materials, with 30% bentonite as a filler. The resulting product contained the following nutrient levels: Nitrogen (N): 0.82%, Phosphorus (P): 4.355%, Potassium (K_2O): 3.97%, Magnesium (MgO): 3.44%, Organic Carbon (C): 15.41%, Iron (Fe): 7,283.8 ppm, and Zinc (Zn): 589 ppm. These values comply with the quality requirements for organic fertilizers as specified in SNI 7763:2024. For further development, subsequent studies should include evaluations of plant responses and assessments of soil nutrient dynamics and changes in microfauna following fertilizer application.

Acknowledgements

This research received financial support from LPPM Tridinanti University in 2025. The author would also like to thank the supporting personnel for their assistance and valuable contributions in this research.

References

Abdulrazik, A., Elsholkami, M., Elkamel, A., & Simon, L. (2017). Multi-products productions from Malaysian oil palm empty fruit bunch (EFB): Analyzing economic potentials from the optimal biomass supply chain. *Journal of Cleaner Production*, *168*, 131–148. https://doi.org/10.1016/j.jclepro.2017.08.088

Abnisa, F., Arami-Niya, A., Wan Daud, W. M. A., Sahu, J. N., & Noor, I. M. (2013). Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis. *Energy Conversion and Management*, *76*, 1073–1082. https://doi.org/10.1016/j.enconman.2013.08.038

Agrahari, R. K., Kobayashi, Y., Tanaka, T. S. T., Panda, S. K., & Koyama, H. (2021). Smart fertilizer management: the progress of imaging technologies and possible implementation of plant biomarkers in agriculture. *Soil Science and Plant Nutrition*, *67*(3), 248–258. https://doi.org/10.1080/00380768.2021.1897479

Ahmed, N., Zhang, B., Chachar, Z., Li, J., Xiao, G., Wang, Q., Hayat, F., Deng, L., Narejo, M. un N., Bozdar, B., & Tu, P. (2024). Micronutrients and their effects on Horticultural crop quality, productivity and sustainability. In *Scientia Horticulturae* (Vol. 323). Elsevier B.V. https://doi.org/10.1016/j.scienta.2023.112512

Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and Its Broad Impacts in Soil Quality and Fertility, Nutrient Leaching and Crop Productivity: A Review. *Agronomy*, *11*(5), 993. https://doi.org/10.3390/agronomy11050993

Anschütz, U., Becker, D., & Shabala, S. (2014). Going beyond nutrition: Regulation of potassium homoeostasis as a common denominator of plant adaptive responses to environment. *Journal of Plant Physiology*, *171*(9), 670–687. https://doi.org/10.1016/j.jplph.2014.01.009

Balafrej, H., Bogusz, D., Triqui, Z.-E. A., Guedira, A., Bendaou, N., Smouni, A., & Fahr, M. (2020). Zinc Hyperaccumulation in Plants: A Review. *Plants*, *9*(5), 562. https://doi.org/10.3390/plants9050562

Balandrán-Valladares, M. I., Cruz-Alvarez, O., Jacobo-Cuellar, J. L., Hernández-Rodríguez, O. A., Flores-Córdova, M. A., Parra-Quezada, R. Á., Sánchez-Chávez, E., & Ojeda-Barrios, D. L. (2021). Changes in nutrient concentration and oxidative metabolism in pecan leaflets at different doses of zinc. *Plant, Soil and Environment*, *67*(1), 33–39. https://doi.org/10.17221/525/2020-PSE

Bianchi, M., Pegoretti, A., & Fredi, G. (2023). An overview of poly(vinyl alcohol) and poly(vinyl pyrrolidone) in pharmaceutical additive manufacturing. *Journal of Vinyl and Additive Technology*, *29*(2), 223–239. https://doi.org/10.1002/vnl.21982

Das, S., Mohanty, S., Sahu, G., Rana, M., & Pilli, K. (2021). Biochar: A Sustainable Approach for Improving Soil Health and Environment. In *Soil Erosion - Current Challenges and Future Perspectives in a Changing World*. IntechOpen. https://doi.org/10.5772/intechopen.97136

de Bang, T. C., Husted, S., Laursen, K. H., Persson, D. P., & Schjoerring, J. K. (2021). The molecular–physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. *New Phytologist*, *229*(5), 2446–2469. https://doi.org/10.1111/nph.17074

Deng, O., Ran, J., Huang, S., Duan, J., Reis, S., Zhang, J., Zhu, Y.-G., Xu, J., & Gu, B. (2024). Managing fragmented croplands for environmental and economic benefits in China. *Nature Food*, *5*(3), 230–240. https://doi.org/10.1038/s43016-024-00938-7

Dikr, W. (2022). Effects of Phosphorus Fertilizer on Agronomic, Grain Yield and Other Physiological Traits of Some Selected Legume Crops. *Journal of Biology, Agriculture and Healthcare*. https://doi.org/10.7176/JBAH/12-12-01

Gao, G., Li, J., Zhang, Y., & Chang, Y.-Z. (2019). *Cellular Iron Metabolism and Regulation* (pp. 21–32). https://doi.org/10.1007/978-981-13-9589-5_2

Gu, B., Zhang, X., Lam, S. K., Yu, Y., van Grinsven, H. J. M., Zhang, S., Wang, X., Bodirsky, B. L., Wang, S., Duan, J., Ren, C., Bouwman, L., de Vries, W., Xu, J., Sutton, M. A., & Chen, D. (2023). Cost-effective mitigation of nitrogen pollution from global croplands. *Nature*, *613*(7942), 77–84. https://doi.org/10.1038/s41586-022-05481-8

Herlihy, J. H., Long, T. A., & McDowell, J. M. (2020). Iron homeostasis and plant immune responses: Recent insights and translational implications. *Journal of Biological Chemistry*, *295*(39), 13444–13457. https://doi.org/10.1074/jbc.REV120.010856

Idris, S. S., Rahman, N. A., & Ismail, K. (2012). Combustion characteristics of Malaysian oil palm biomass, sub-bituminous coal and their respective blends via thermogravimetric analysis (TGA). *Bioresource Technology*, *123*, 581–591. https://doi.org/10.1016/j.biortech.2012.07.065

Jia, Y., Hu, Z., Ba, Y., & Qi, W. (2021). Application of biochar-coated urea controlled loss of fertilizer nitrogen and increased nitrogen use efficiency. *Chemical and Biological Technologies in Agriculture*, *8*(1), 3. https://doi.org/10.1186/s40538-020-00205-4

Jiang, Z., Vancov, T., Fang, Y., Tang, C., Zhang, W., Xiao, M., Song, X., Zhou, J., Ge, T., Cai, Y., Yu, B., White, J. C., & Li, Y. (2025). Sustained superiority of biochar over straw for enhancing soil biological-phosphorus via the mediation of phoD-harboring bacteria in subtropical Moso bamboo forests. *Forest Ecology and Management*, *584*, 122606. https://doi.org/10.1016/j.foreco.2025.122606

Jonbi, J., Fulazzaky, M. A., Simatupang, P. H., Tjahjani, A. R. I., & Suraedi, D. (2025). Palm oil boiler ash as a viable substitute for cement. *Results in Engineering*, *28*. https://doi.org/10.1016/j.rineng.2025.107616

Journal of Agroindustrial Development and Innovation
Vol.1, No.1, May 2026, pp.01-10
ISSN: xxxx-xxxx **DOI:** https://doi.org/xx

Kaavessina, M., Distantina, S., & Shohih, E. N. (2021). A Slow-Release Fertilizer of Urea Prepared via Melt Blending with Degradable Poly(lactic acid): Formulation and Release Mechanisms. *Polymers*, *13*(11), 1856. https://doi.org/10.3390/polym13111856

Kabiri, S., Degryse, F., Tran, D. N. H., da Silva, R. C., McLaughlin, M. J., & Losic, D. (2017). Graphene Oxide: A New Carrier for Slow Release of Plant Micronutrients. *ACS Applied Materials & Interfaces*, *9*(49), 43325–43335. https://doi.org/10.1021/acsami.7b07890

Kamerlin, S. C. L., Sharma, P. K., Prasad, R. B., & Warshel, A. (2013). Why nature really chose phosphate. *Quarterly Reviews of Biophysics*, *46*(1), 1–132. https://doi.org/10.1017/S0033583512000157

Khan, M. A., Kim, K.-W., Mingzhi, W., Lim, B.-K., Lee, W.-H., & Lee, J.-Y. (2008). Nutrient-impregnated charcoal: an environmentally friendly slow-release fertilizer. *The Environmentalist*, *28*(3), 231–235. https://doi.org/10.1007/s10669-007-9133-5

Kirkby, E. A. (2023). Introduction, definition, and classification of nutrients. In *Marschner's Mineral Nutrition of Plants* (pp. 3–9). Elsevier. https://doi.org/10.1016/B978-0-12-819773-8.00016-2

Kumar, S. A., Kaniganti, S., Hima Kumari, P., Sudhakar Reddy, P., Suravajhala, P., P, S., & Kishor, P. B. K. (2024). Functional and biotechnological cues of potassium homeostasis for stress tolerance and plant development. *Biotechnology and Genetic Engineering Reviews*, *40*(4), 3527–3570. https://doi.org/10.1080/02648725.2022.2143317

Lateef, A., Nazir, R., Jamil, N., Alam, S., Shah, R., Khan, M. N., & Saleem, M. (2016). Synthesis and characterization of zeolite based nano–composite: An environment friendly slow release fertilizer. *Microporous and Mesoporous Materials*, *232*, 174–183. https://doi.org/10.1016/j.micromeso.2016.06.020

Li, J., Cao, X., Jia, X., Liu, L., Cao, H., Qin, W., & Li, M. (2021). Iron Deficiency Leads to Chlorosis Through Impacting Chlorophyll Synthesis and Nitrogen Metabolism in Areca catechu L. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.710093

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J. M., & Zhao, B. (2018). Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. *Soil and Tillage Research*, *175*, 281–290. https://doi.org/10.1016/j.still.2017.08.008

Mandiri. (2012). *Manual Pelatihan Teknologi Energi Terbarukan*. DANIDA.

Nabila, R., Hidayat, W., Haryanto, A., Hasanudin, U., Iryani, D. A., Lee, S., Kim, S., Kim, S., Chun, D., Choi, H., Im, H., Lim, J., Kim, K., Jun, D., Moon, J., & Yoo, J. (2023). Oil palm biomass in Indonesia: Thermochemical upgrading and its utilization. *Renewable and Sustainable Energy Reviews*, *176*, 113193. https://doi.org/10.1016/j.rser.2023.113193

Otiende, M. A., Fricke, K., Nyabundi, J. O., Ngamau, K., Hajirezaei, M. R., & Druege, U. (2021). Involvement of the auxin–cytokinin homeostasis in adventitious root formation of rose cuttings as affected by their nodal position in the stock plant. *Planta*, *254*(4), 65. https://doi.org/10.1007/s00425-021-03709-x

Pandebesie, E. S., & Rayuanti, D. (2013). Pengaruh Penambahan Sekam Pada Proses Pengomposan Sampah Domestik. Jurnal Lingkungan Tropis. *Jurnal Lingkungan Tropis*, *6*(1), 31–40.

Peng, Y. Y., Liao, L. L., Liu, S., Nie, M. M., Li, J., Zhang, L. D., Ma, J. F., & Chen, Z. C. (2019). Magnesium Deficiency Triggers SGR–Mediated Chlorophyll Degradation for Magnesium Remobilization. *Plant Physiology*, *181*(1), 262–275. https://doi.org/10.1104/pp.19.00610

Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of Zinc Nutrition for Increasing Zinc Availability, Uptake, Yield, and Quality of Maize (Zea Mays L.) Grains: An Overview. *Communications in Soil Science and Plant Analysis*, *51*(15), 2001–2021. https://doi.org/10.1080/00103624.2020.1820030

Tang, R.-J., & Luan, S. (2020). Rhythms of magnesium. *Nature Plants*, *6*(7), 742–743. https://doi.org/10.1038/s41477-020-0706-3

Tripathi, R., Tewari, R., Singh, K. P., Keswani, C., Minkina, T., Srivastava, A. K., De Corato, U., & Sansinenea, E. (2022). Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.883970

Vélez-Bermúdez, I. C., & Schmidt, W. (2023). Plant strategies to mine iron from alkaline substrates. *Plant and Soil*, *483*(1–2), 1–25. https://doi.org/10.1007/s11104-022-05746-1

White, P. J., Broadley, M. R., El-Serehy, H. A., George, T. S., & Neugebauer, K. (2018). Linear relationships between shoot magnesium and calcium concentrations among angiosperm species are associated with cell wall chemistry. *Annals of Botany*, *122*(2), 221–226. https://doi.org/10.1093/aob/mcy062

Widarti, B. N., Wardhini, W. K., & Sarwono, E. (2015). PENGARUH RASIO C/N BAHAN BAKU PADA PEMBUATAN KOMPOS DARI KUBIS DAN KULIT PISANG. *Jurnal Integrasi Proses*, *5*, 75–80.

Zhang, H., Xing, L., Liang, H., Liu, S., Ding, W., Zhang, J., & Xu, C. (2023). Preparation and characterization of biochar-based slow-release nitrogen fertilizer and its effect on maize growth. *Industrial Crops and Products*, *203*, 117227. https://doi.org/10.1016/j.indcrop.2023.117227