ASEAN Journal of Science and Engineering

Journal homepage: http://ejournal.upi.edu/index.php/AJSE/

Production of Microparticle Biochar from Pomegranate Peel Under Difference Pyrolysis Temperature and Its Potential as A Soil Amendment to Support Sustainable Development Goals (SDGs)

Ali Rahmat [1], Hidayat Hidayat[1], S. Sukamto[2], Yudia Azmi[3], Angus Onwudiwe Ikeh[4], Abdul Mutolib[5,]*

[1]Badan Riset dan Inovasi Nasional, Indonesia
[2]Universitas Nahdhatul Ulama Yogyakarta, Yogyakarta, Indonesia
[3]Institut Teknologi Perkebunan Pelalawan Indonesia, Pelalawan, Indonesia
[4]University of Agriculture and Environmental Sciences, Umuagwo, Nigeria
[5]Universitas Siliwangi, Tasikmalaya, Indonesia
*Correspondence: E-mail: abdul.mutolib@unsil.ac.id

ABSTRACT

Pomegranate peel, a common agro-industrial byproduct, was studied for its conversion into microparticle biochar through pyrolysis at two temperature settings. The peel was oven-dried, pyrolyzed, ground, and analyzed using spectroscopy, microscopy, and conductivity methods. Biochar obtained at higher temperature showed lower yield but improved physicochemical qualities, including larger surface area, higher porosity, more alkaline pH, and enhanced electrical conductivity. These changes were caused by intensified thermal treatment, which promoted devolatilization, mineral concentration, and the formation of aromatic carbon structures. The presence of functional groups and enriched minerals supports the biochar's role in improving soil fertility, nutrient retention, and overall soil health. This research also aligns with Sustainable Development Goals (SDGs): promoting waste valorization and circular use of resources (SDG 12), improving soil productivity for food systems (SDG 2), contributing to climate change mitigation through carbon sequestration (SDG 13), and fostering ecosystem restoration (SDG 15).

ARTICLE INFO

Article History:
Submitted/Received 20 Jun 2025
First Revised 24 Jul 2025
Accepted 21 Sep 2025
First Available online 22 Sep 2025
Publication Date 01 Dec 2026

Keyword:
Carbon sequestration,
Chi River basin,
Microbial communities,
Spirogyra,
Sustainable Development Goals (SDGs).

1. INTRODUCTION

The global agro-industry generates over two billion tons of agricultural waste annually, with a significant portion originating from fruit processing sectors such as pomegranate-based industries [1]. Pomegranate (Punica granatum L.) is widely cultivated in both temperate and tropical regions and valued across food, pharmaceutical, and cosmetic domains due to its bioactive compounds [2]. However, approximately 40–50% of the fruit's weight comprises peel, which is typically discarded, leading to environmental pollution and underutilization of a potentially valuable resource [3].

Composting, though commonly practiced for organic waste management, has several limitations. These include slow degradation, low nutrient value, unpleasant odor, and limited pathogen control [4–6]. An emerging alternative is the conversion of agricultural residues into biochar, a carbon-rich, porous material produced via pyrolysis under limited oxygen conditions [7]. Biochar has been shown to improve soil fertility, enhance water retention, stabilize organic matter, and act as a long-term carbon sink [8–12]. Many reports regarding biochar have been well-documented [13-22]. Various biomass sources such as rice husks, olive pits, and wood residues have yielded promising biochar properties, including increased porosity, alkalinity, and cation exchange capacity [23].

The pyrolysis process (particularly temperature) greatly influences the yield, pore structure, chemical composition, and surface properties of biochar [24]. Lower temperatures typically preserve organic matter, while higher temperatures promote aromatization and mineral concentration [8]. Moreover, engineering biochar into microparticle sizes has been proven to increase its adsorption efficiency and reduce mobility in the environment, making it more suitable for agricultural applications [25–27].

Given the high extractive and lignin content of pomegranate peel [28], it holds potential for the production of high-quality microparticle biochar. However, comprehensive data on how pyrolysis temperature affects the physical and chemical traits of pomegranate peel-derived biochar remain limited.

This study investigates the physicochemical properties of microparticle biochar derived from pomegranate peel pyrolyzed at two different temperatures and evaluates its potential as a soil amendment. The novelty lies in the integration of temperature-specific characterization with a focus on microstructural development and nutrient composition. The research contributes to Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land) by promoting waste valorization, carbon stabilization, and soil restoration strategies.

2. METHODS

Figure 1 illustrates the overall procedure used to produce microparticle biochar from pomegranate peel, beginning with sample preparation and culminating in physicochemical characterization. Pomegranate fruits were sourced from local markets, and the peels were separated manually. The peel residues were rinsed with tap water to remove surface impurities and cut into smaller segments to facilitate drying. These segments were oven-dried at 105 °C for 24 hours to eliminate moisture and prepare the biomass for pyrolysis. The dried samples were placed into porcelain crucibles for thermal processing.

The pyrolysis process was conducted in a muffle furnace at two distinct temperatures: 300 °C and 400 °C. Each pyrolysis cycle lasted four hours. The resulting biochar samples were labeled as PPB300 and PPB400, corresponding to the temperature used. After cooling, the biochars were ground and sieved through a 90 μm mesh to produce microparticles. This size reduction technique was employed to improve surface accessibility and reduce particle mobility, contributing to enhanced soil interaction, in line with the goals of sustainable agriculture (SDG 2) and waste valorization (SDG 12).

Figure 1. Process sequence for producing powdered biochar from pomegranate peel.

For characterization, scanning electron microscopy (SEM) was used to observe surface morphology. The Brunauer–Emmett–Teller (BET) method was applied to assess surface area and pore characteristics. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify functional groups, while X-Ray Diffraction (XRD) was used to determine the crystalline structure of the samples. The elemental composition was analyzed using X-ray fluorescence (XRF) with an Omnian ED-XRF Panalytical Epsilon 3 XLE. Additionally, pH and electrical conductivity (EC) of the biochar were measured using a HORIBA LAQUAtwin instrument.

All measurements were conducted in duplicate for consistency, and the results were analyzed descriptively to compare the influence of pyrolysis temperature on biochar properties.

3. RESULTS AND DISCUSSION

Figure 2 presents the yield of biochar derived from pomegranate peel under two pyrolysis temperature conditions. Detailed information regarding the effect of temperature is explained elsewhere [29]. At 300 °C, the yield was 62.14%, which dropped significantly to 47.95% at 400 °C. This decline is attributable to the increased severity of thermal decomposition processes at higher temperatures, particularly devolatilization and the cracking of organic compounds. Lower temperatures preserve more volatile matter, whereas higher thermal input promotes the breakdown of hemicellulose and cellulose and the rearrangement of carbon structures into more stable forms. This behavior aligns with observations reported previously [8, 30], who documented similar decreases in yield for pomegranate and other lignocellulosic materials. The relatively high lignin content in pomegranate peel (22.1%) aids in char stability, while the abundance of extractives (57.9%) contributes to substantial volatile losses, explaining the reduction in yield at 400 °C [28].

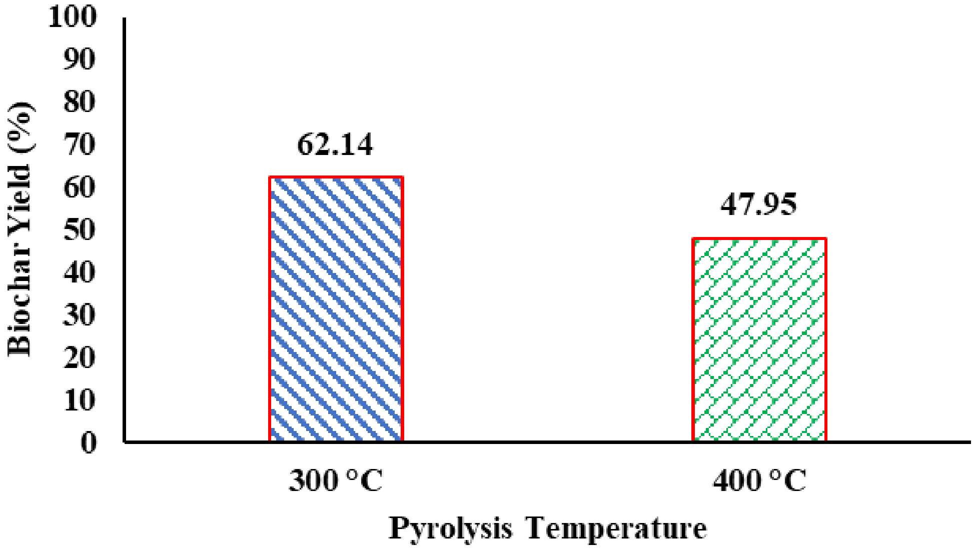

Figure 2. Biochar yield of pomegranate peel at different pyrolysis temperatures.

Figure 3 and **Table 1** show the surface characteristics of the biochars produced at the two pyrolysis temperatures. SEM images illustrate morphological changes from a more compact and irregular structure at 300 °C to a rougher surface with increased pore development at 400 °C. The rougher and more porous structure of PPB400 suggests a higher level of internal decomposition and carbon reorganization. These changes are further validated by the BET analysis. Surface area increased from 10.73 m²/g (PPB300) to 13.26 m²/g (PPB400), while pore volume rose from 0.026 to 0.034 cc/g. Interestingly, the average pore radius decreased slightly from 19.41 Å to 17.29 Å, indicating a narrowing of pores while overall porosity increased. These changes occur because higher pyrolysis temperatures promote the release of volatile gases, resulting in expanded and more defined pores within the char matrix [31, 32]. The improved surface properties support greater adsorption capacity and water retention potential, aligning with the goals of SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

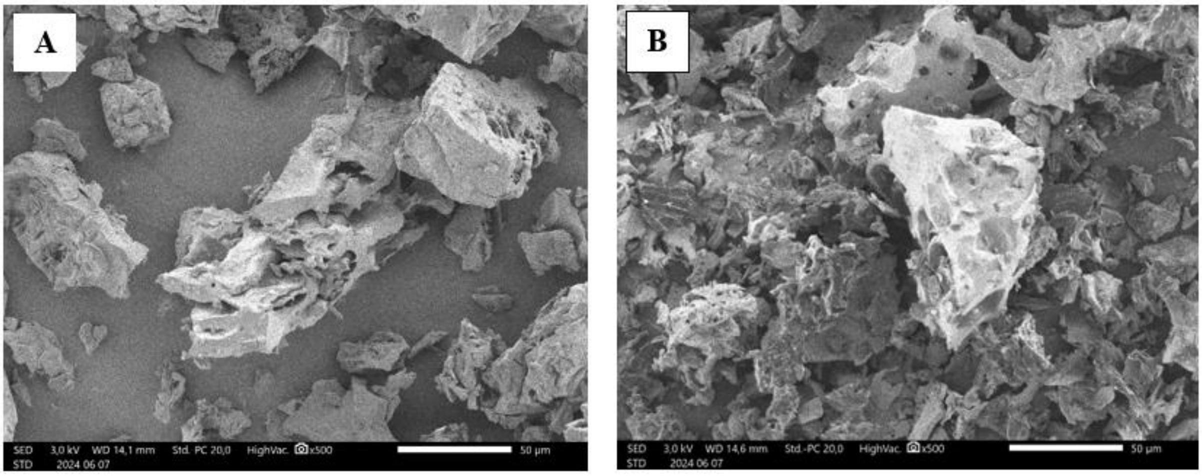

Figure 3. Surface morphology of pomegranate peel biochar at different temperatures (A) 300 °C (B) 400 °C.

Figure 4 shows the FTIR spectra of the biochar samples. Detailed information regarding FTIR is explained elsewhere [33-35]. At both temperatures, broad peaks in the 3223–3431 cm^{-1} range correspond to hydroxyl (–OH) stretching vibrations. The intensity of these peaks decreased at the higher temperature, indicating a loss of polar functional groups as pyrolysis progressed. Absorption bands near 1622.70 and 1574.65 cm^{-1} correspond to aromatic C=C stretching, suggesting the formation of stable aromatic structures. The peak at 2926.55 cm^{-1} is attributed to aliphatic C–H stretching vibrations, while additional bands indicate the presence of C–N, $-NH_2$, and C–C functionalities. As pyrolysis temperature increases, thermal degradation of hemicellulose, cellulose, and partially lignin leads to the elimination of oxygenated groups and formation of condensed aromatic domains [20, 21, 22]. Although the loss of some functional groups reduces specific reactivity, the resulting carbon structure becomes more chemically stable, contributing to long-term carbon sequestration (SDG 13) and sustained soil conditioning effects.

Table 1. BET surface properties of pomegranate peel biochar at different pyrolysis temperatures.

Biochar Product	Surface Area (m²/g)	Pore Volume (cc/g)	Pore Radius (Å)
PPB300	10.726	0.026	19.410
PPB400	13.256	0.034	17.285

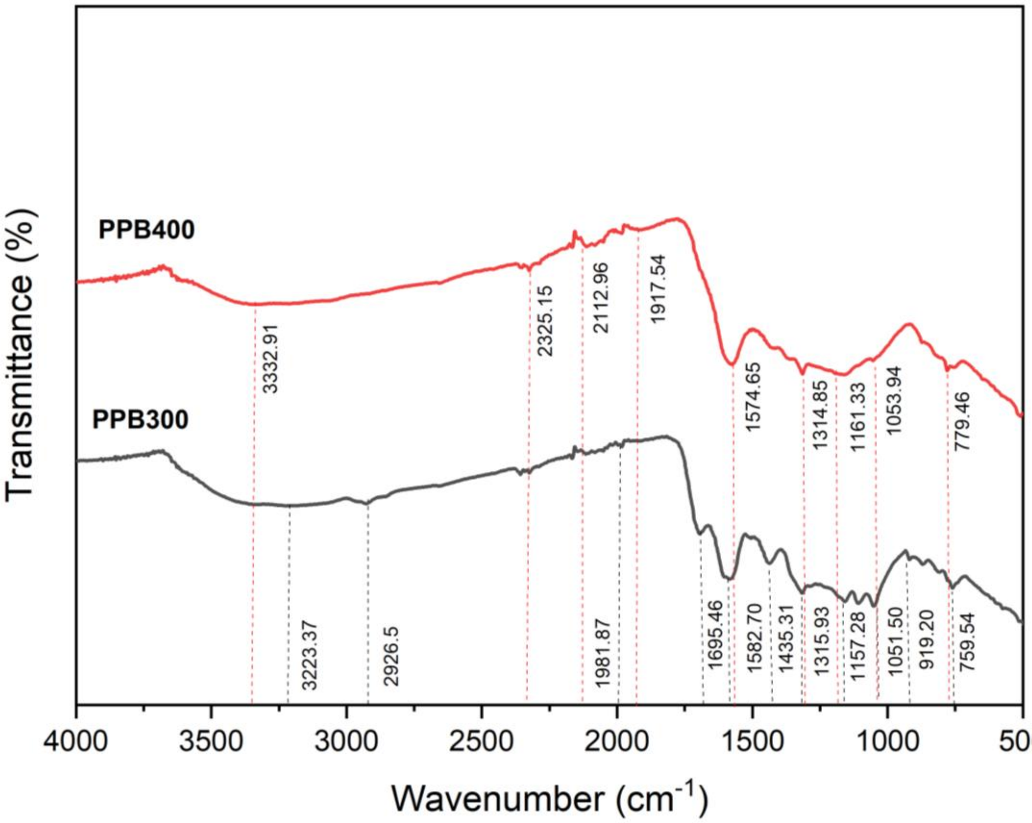

Figure 4. FTIR spectra of pomegranate peel biochar at different pyrolysis temperatures (A) 300 °C and (B) 400 °C.

Figure 5 presents the XRD patterns of the two biochar samples. Detailed information regarding XRD is explained elsewhere [36]. Broad diffraction humps were observed between 15 and 35° 2θ, which correspond to the (002) planes of turbostratic carbon, characteristic of disordered graphite-like structures. Peaks observed around 14°, 23°, and 35° indicate partial retention of crystalline cellulose, which diminishes with increased temperature. These broad and diffused features suggest a semi-amorphous structure, where amorphous carbon dominates but residual crystalline regions remain. The peaks become slightly sharper in PPB400, reflecting the onset of more ordered structural domains as thermal energy facilitates carbon atom rearrangement [37–39]. This evolution toward structural ordering enhances the mechanical stability of biochar and contributes to the formation of persistent carbon pools in the soil, thereby reinforcing the role of biochar in climate mitigation strategies (SDG 13).

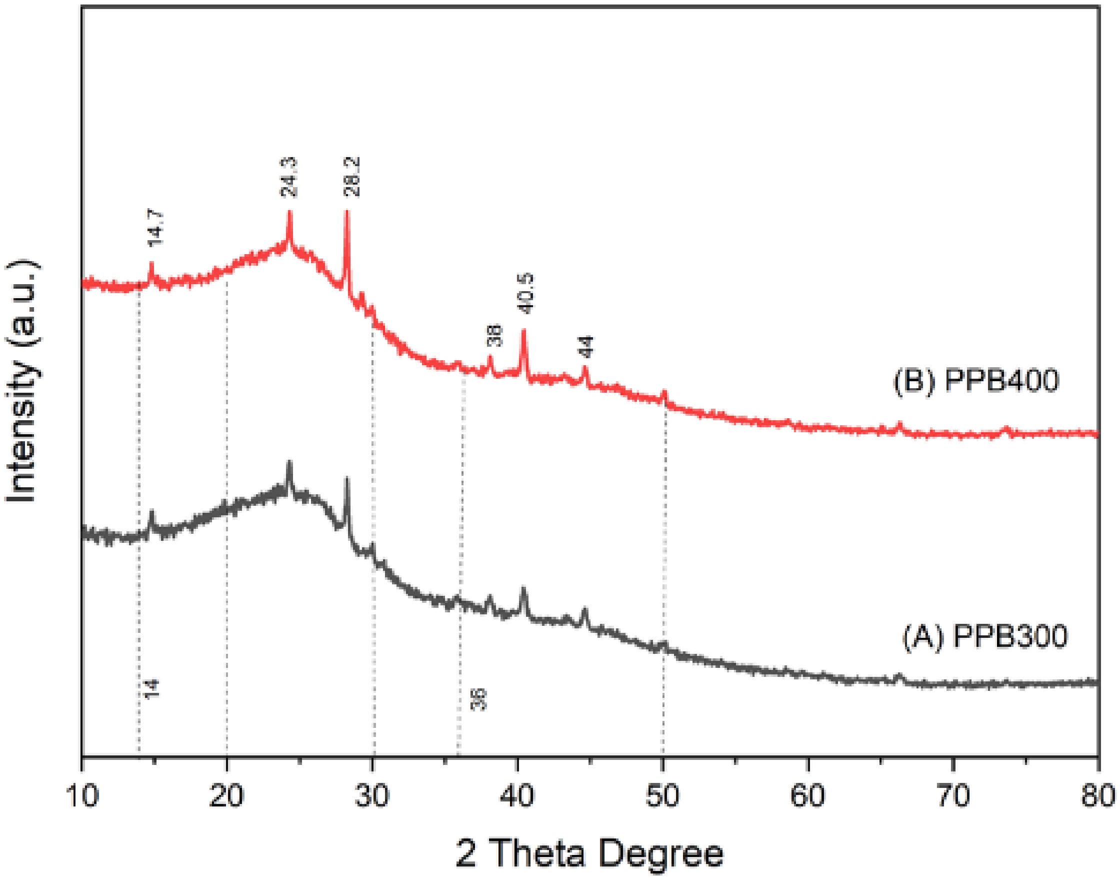

Figure 5. XRD patterns of (A) PPB300 and (B) PPB400.

Table 2 summarizes the elemental composition of the biochar samples determined via X-ray fluorescence (XRF). Calcium (Ca), phosphorus (P), and iron (Fe) contents increased at 400 °C, while potassium (K), sulfur (S), manganese (Mn), bromine (Br), zinc (Zn), and copper (Cu) concentrations decreased. These variations result from the volatilization of certain elements at high temperatures and the relative enrichment of thermally stable minerals. For instance, the reduction of K and S reflects their lower thermal stability and tendency to evaporate during pyrolysis. Meanwhile, the concentration of Ca and Fe increased due to their resistance to volatilization, making them more prominent in the residue. This transformation pattern is consistent with studies on other biomass sources such as rice straw and sugarcane bagasse [40,41]. The enriched mineral profile of high-temperature biochar suggests its potential to act as a source of essential nutrients, particularly for acidic or mineral-deficient soils (SDG 2 and 15).

Table 3 presents the pH and electrical conductivity (EC) of the biochars produced. The pH of PPB300 was slightly acidic at 6.1, while PPB400 exhibited an alkaline pH of 8.2. Similarly, the EC value increased from 1314 µS/cm to 1963 µS/cm as the pyrolysis temperature increased. The higher pH and EC in PPB400 reflect the accumulation of alkali minerals and soluble salts that result from the decomposition of organic matter at elevated temperatures [42]. These changes enhance the ability of biochar to neutralize soil acidity and increase the availability of plant nutrients. The alkaline nature of PPB400 is especially beneficial for acidic tropical soils, offering a sustainable approach to soil amelioration (SDG 15). Moreover, increased EC may stimulate microbial activity and improve nutrient uptake, supporting broader goals of agricultural productivity and food security (SDG 2).

Table 2. Elemental content of pomegranate peel biochar.

No	Element	PPB300	PPB400
1	K (%)	64.40	59.94
2	Ca (%)	32.24	37.07
3	P (%)	1.07	1.28
4	S (%)	0.90	0.25
5	Fe (%)	0.46	0.96
6	Mn (%)	0.29	0.087
7	Br (ppm)	966.1	713.0
8	Zn (ppm)	827.5	626.9
9	Cu (ppm)	715.6	689.6
10	Rb (%)	0.224	0.023
11	Sr (ppm)	754.1	497

Table 3. pH and electrical conductivity of pomegranate peel biochar.

Observation Variables	Aquades	PPB 300°C	PPB 400°C
pH	7.2	6.1	8.2
EC/Electric conductivity (µS/cm)	11	1314	1963

The combination of increased porosity, mineral enrichment, alkaline pH, and structural stability in high-temperature biochar confirms its potential as a multifunctional soil amendment. These properties contribute to improving physical soil structure, enhancing nutrient availability, and promoting long-term carbon stabilization. The valorization of pomegranate peel into biochar exemplifies circular economy practices by transforming agricultural waste into a high-value input for sustainable farming systems, aligning directly with SDG 12 (Responsible Consumption and Production). Furthermore, by enhancing soil resilience and reducing dependence on chemical fertilizers, biochar supports ecological restoration and environmental sustainability (SDGs 13 and 15).

The physicochemical transformations observed in the pomegranate peel biochar across different pyrolysis temperatures provide important insights into how thermal processing conditions influence its effectiveness as a soil amendment. The temperature-induced differences in yield, surface morphology, functional groups, and elemental composition directly affect the interaction between biochar and soil systems. Specifically, higher pyrolysis temperature promotes more significant structural rearrangement and elemental reconfiguration, resulting in a biochar product that is more porous, alkaline, and mineral-rich.

The increased porosity and surface area observed in PPB400 are particularly important for soil water dynamics and microbial habitat. Highly porous biochar enhances soil aeration and water-holding capacity, especially in sandy soils or degraded agricultural fields. These properties contribute to reduced irrigation requirements and greater drought resilience for crops, which is vital for smallholder farmers facing erratic rainfall and climate stress.

Moreover, the rough and porous surfaces of high-temperature biochar offer more binding sites for nutrients and microbial colonization, facilitating nutrient retention and microbial activity in the rhizosphere. This effect supports SDG 2 (Zero Hunger) through enhanced crop productivity and SDG 13 (Climate Action) by improving carbon efficiency in soil–plant systems.

The change in pH from slightly acidic in PPB300 to alkaline in PPB400 has notable agronomic implications. In tropical and subtropical regions, soils often exhibit low pH due to high rainfall and prolonged weathering. Such acidic conditions can limit nutrient availability and increase aluminum toxicity, inhibiting root growth and nutrient uptake. The application of alkaline biochar such as PPB400 helps neutralize soil acidity, increase cation exchange capacity, and make essential nutrients more bioavailable. These benefits reduce the need for chemical liming and synthetic fertilizers, promoting more environmentally friendly and cost-effective soil management strategies, thus aligning with SDG 12 (Responsible Consumption and Production).

The substantial increase in electrical conductivity from 1314 µS/cm to 1963 µS/cm further indicates the concentration of soluble ions in PPB400. Elevated EC is often associated with improved nutrient content, especially when biochar is applied at appropriate rates. However, extremely high EC values can pose a risk of salinity buildup in sensitive soils. Therefore, field application of biochar must be guided by context-specific assessments, including soil type, crop species, and irrigation patterns. In moderate doses, biochar with high EC, such as PPB400, can serve as a carrier for nutrients like potassium, calcium, and phosphorus, reducing nutrient leaching and improving fertilizer-use efficiency. This nutrient retention capacity is critical for enhancing productivity in low-input systems and degraded lands, contributing again to SDGs 2 and 15.

From a chemical standpoint, the loss of volatile functional groups and the increase in aromaticity with rising temperature suggest that PPB400 is more chemically stable and resistant to microbial decomposition. This stability means that the carbon in PPB400 is likely to remain in soil for longer periods, acting as a long-term carbon sink. Such persistence directly supports efforts to mitigate greenhouse gas emissions through terrestrial carbon sequestration, a key component of SDG 13. In contrast, PPB300 retains more labile functional groups, which may degrade more quickly in soil and contribute to short-term nutrient cycling rather than long-term stabilization. Thus, depending on the intended purpose (nutrient cycling versus carbon storage) the pyrolysis temperature can be selected to produce functionally targeted biochar.

Elemental data in **Table 2** show that potassium content decreased from 64.40% in PPB300 to 59.94% in PPB400, while calcium increased from 32.24% to 37.07%. Potassium is a mobile element that volatilizes easily at higher temperatures, explaining its decline in PPB400. Conversely, calcium and iron are more thermally stable, and their relative concentration increases as other organic matter is lost. This shift indicates that high-temperature biochar is enriched in more recalcitrant and agriculturally beneficial minerals. Calcium, for instance, plays a key role in root development, soil aggregation, and cell wall formation. Its higher availability in PPB400 could enhance plant structural integrity and stress tolerance, offering both agronomic and environmental advantages.

Phosphorus, although present in smaller quantities, also showed an increase from 1.07% to 1.28% with rising temperature. Phosphorus in biochar is generally less prone to leaching and can be released gradually, providing a slow-release source of this critical nutrient. As phosphorus reserves worldwide are depleting and phosphorus fertilizers are becoming more expensive, the role of biochar as an alternative phosphorus source gains significance. Biochar-enhanced phosphorus availability supports root elongation and early plant vigor, which are essential for crop establishment and resilience under stressful growing conditions. These contributions are essential for achieving SDG 2 through sustainable intensification.

In the context of soil remediation, the presence of micronutrients such as iron (Fe), manganese (Mn), and copper (Cu) plays an auxiliary role in improving soil fertility. While these elements were found in smaller quantities and tended to decline at higher temperature, their availability in biochar can be beneficial for correcting micronutrient deficiencies in tropical soils. However, some trace elements, such as bromine (Br) and rubidium (Rb), which were detected in parts per million levels, require further toxicological evaluation before recommending large-scale biochar application, especially in sensitive agroecosystems. Future studies could assess the bioavailability and mobility of these elements under different field conditions.

Importantly, the biochar derived from pomegranate peel also demonstrates environmental benefits by diverting fruit-processing waste from open dumping or uncontrolled burning. This valorization route transforms agricultural byproducts into a valuable input for soil management, representing a circular bioeconomy strategy that reduces waste and contributes to rural livelihoods. Such strategies reinforce the goals of SDG 12 (Responsible Consumption and Production) by maximizing the utility of biomass resources and reducing environmental burden.

The cumulative findings of this study provide a framework for tailoring biochar characteristics to meet specific agronomic and environmental needs. For example, low-temperature biochar with higher volatile content may be suited for immediate nutrient release, while high-temperature biochar may be preferred for soil pH correction, long-term carbon stabilization, and structural enhancement. This flexibility allows stakeholders (from smallholder farmers to agro-industrial processors) to adopt biochar technologies that align with their production systems and resource constraints. Moreover, integrating biochar into broader land management programs can complement composting, organic mulching, and cover cropping, creating multifunctional and climate-resilient agricultural landscapes.

In line with SDG 15 (Life on Land), biochar application can help restore degraded lands by improving soil physical properties, microbial diversity, and organic matter content. This is particularly relevant in regions suffering from desertification, erosion, or nutrient mining, where traditional soil amendments are either unavailable or unaffordable. The use of locally available feedstocks such as pomegranate peel for biochar production reduces dependence on external inputs, promotes local innovation, and supports environmental justice by enabling marginalized communities to enhance their soil capital.

From a policy perspective, the outcomes of this study may inform the development of national guidelines or incentives for biochar adoption, particularly in regions with abundant fruit processing waste. Governments and extension services could provide technical support for small-scale pyrolysis units and promote public-private partnerships to commercialize biochar production. Training programs on sustainable biomass utilization and biochar application could also empower rural communities to build capacity around climate-smart agriculture. These systemic interventions would not only support SDGs 2, 12, 13, and 15 but also generate co-benefits in employment, biodiversity, and climate resilience. This study adds new information regarding SDGs, as reported elsewhere (**Table 4**).

Table 4. Previous studies on SDGs.

No	Title	Ref
1	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	[43]

Table 4 (continue). Previous studies on SDGs.

No	Title	Ref
2	Sustainable packaging: Bioplastics as a low-carbon future step for the SDGs	[44]
3	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting SDGs	[45]
4	HIRADC for workplace safety in manufacturing: A risk-control framework and bibliometric review to support SDGs	[46]
5	Techno-economic analysis of production ecobrick from plastic waste to support SDGs	[47]
6	Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia's green tourism policy and the SDGs	[48]
7	Definition and role of sustainable materials in reaching global SDGs completed with bibliometric analysis	[49]
8	Bibliometric insight into materials research trends and innovation to support SDGs	[50]
9	Physical adaptation of college students in high-altitude training to support SDGs	[51]
10	Enhancing job satisfaction through HRIS and communication: A commitment-based approach to SDGs	[52]
11	Enhancing innovative thinking through theory-based instructional model to support SDGs	[53]
12	Influence of self-efficacy on affective learning outcomes in social studies education toward achieving SDGs	[54]
13	Enhancing occupational identity and self-efficacy through self-education in art/design aligned with SDGs	[55]
14	Integrating generative AI-based multimodal learning in education to enhance literacy aligned with SDGs	[56]
15	Dataset on Sulawesi schools and cultural implications to support SDGs	[57]
16	Enhancing professional readiness in vocational education aligned with SDGs	[58]
17	School feeding program and SDGs in education: Linking food security to learning outcomes	[59]
18	Influence of eco-friendly packaging on consumer interest to meet SDGs	[60]
19	SDG 12 implementation through lemon commodities and waste reduction	[61]
20	Mediterranean diet patterns and sustainability to support SDGs	[62]
21	Education on food diversification through infographic to improve SDGs	[63]
22	Safe food treatment technology to achieve SDG zero hunger and optimal health	[64]
23	Student awareness of sustainable diet and carbon footprint reduction to support SDGs 2030	[65]

Overall, the use of pomegranate peel to produce microparticle biochar demonstrates a practical and scalable solution to agricultural waste management and soil degradation. The temperature-specific variations in biochar properties offer flexibility for multiple applications, whether the goal is to enhance crop yields, improve soil chemistry, or sequester atmospheric carbon. By linking biochar research with sustainable development goals, this study advances both scientific understanding and real-world applicability of biochar-based interventions.

4. CONCLUSION

This study confirmed that pyrolysis temperature significantly influences the physicochemical properties of microparticle biochar derived from pomegranate peel. Higher pyrolysis temperature resulted in lower yield but improved surface area, porosity, mineral concentration, and pH, alongside the development of stable aromatic structures. These transformations occurred because elevated thermal conditions promoted devolatilization, mineral enrichment, and carbon rearrangement. The resulting biochar displayed properties suitable for enhancing acidic soils, improving nutrient retention, and contributing to long-term carbon sequestration. As such, pomegranate peel biochar offers a sustainable strategy for agro-waste valorization, supporting responsible production practices and soil rehabilitation. These findings contribute directly to the achievement of several Sustainable Development Goals, particularly those related to food security (SDG 2), waste management (SDG 12), climate action (SDG 13), and land restoration (SDG 15).

5. ACKNOWLEDGMENT

We gratefully acknowledge the support of the Badan Riset dan Inovasi Nasional (BRIN) and Universitas Muhammadiyah Yogyakarta (UMY) Research Program, which enabled the successful completion of this study.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

7. REFERENCES

[1] Singh, R., Das, R., Sangwan, S., Rohatgi, B., Khanam, R., Dr, G., Das, S., Lyngdoh, Y. A., Langyan, S., Hukla, A., Shrivastava, M., and Misra, S. (2021). Agricultural waste generation and utilization. *Environmental Sustainability*, *4*, 619.

[2] Chen, Y., Yang, J., and Abbas, A. (2023). Pomegranate applications in health and cosmetics. *Toxics*, *11*, 440.

[3] Rashtbari, Y., Hazrati, S., Azari, A., Afshin, S., Fazlzadeh, M., and Vosoughi, M. (2020). Pomegranate peel waste characterization. *Advanced Powder Technology*, *31*, 1612–1620.

[4] Sarjiyah, Aini, L. N., and Hamdani, M. R. (2024). Organic waste treatment strategies. *IOP Conference Series: Earth and Environmental Science*, *1417*, 012042.

[5] Dewi, S. S., Mulyono, M., Koeswara, D. D., and Hartanto, T. (2024). Limitations in composting. *IOP Conference Series: Earth and Environmental Science*, *1417*, 012036.

[6] Ayilara, M. S., Olanrewaju, O. S., Babalola, O. O., and Odeyemi, O. (2020). Composting and biochar comparison. *Sustainability*, *12*, 4456.

[7] Yadav, R., and Ramakrishna, W. (2023). Biochar for sustainable agriculture. *Sustainability*, *15*, 13421.

[8] Phadtare, P. D., and Kalbande, S. R. (2022). Biochar yield and pyrolysis dynamics. *International Journal of Environment and Climate Change*, *12*, 1010–1019.

[9] Hariyono, B. H., Isnawan, M., Mulyono, M., and Darmawan, B. E. (2023). Biochar applications in agriculture. *IOP Conference Series: Earth and Environmental Science*, *1287*, 012014.

[10] Sarjiyah, Aini, L. N., and Dewi, R. S. (2024). Soil fertility enhancement with biochar. *IOP Conference Series: Earth and Environmental Science*, *1417*, 012012.

[11] Mulyono, M., Merliana, A., Isnawan, B. H., and Hartanto, T. (2024). Biochar production from tropical residues. *IOP Conference Series: Earth and Environmental Science*, *1417*, 012013.

[12] Murtaza, G., Ahmed, Z., Usman, M., Tariq, W., Ullah, Z., Shareef, M., Iqbal, H., Waqas, M., Tariq, A., Wu, Y., Zhang, Z., and Ditta, A. (2021). Biochar impact on soil and plant health. *Journal of Plant Nutrition*, *44*, 1677–1689.

[13] Nandiyanto, A. B. D., Putri, A. E., Fiandini, M., Ragadhita, R., and Kurniawan, T. (2025). Biochar microparticles from pomegranate peel waste: Literature review and experiments in isotherm adsorption of ammonia. *Applied Science and Engineering Progress*, *18*(1), 7506.

[14] Farobie, O., Amrullah, A., Fattiasari, W., Nandiyanto, A.B.D., Ernawati, L., Karnjanakom, S., Lee, S.H., Selvasembian, R., Azelee, N. I. W., and Aziz, M. (2024). Co-pyrolysis of plastic waste and macroalgae Ulva lactuca, a sustainable valorization approach towards the production of bio-oil and biochar. *Results in Engineering*, *24*, 103098.

[15] Mubarokah, S. L., Anwar, S., Nisa, K., Miftah, H., Hastuti, A., and Nandiyanto, A. B. D. (2024). Bibliometrics study on agro-economy of biochar. *Journal of Engineering Science and Technology*, *19*, 142–152.

[16] Martin, A. Y., Roestamy, M., Qolyubi, A. T., Hakim, A. L., Nandiyanto, A. B. D. (2024). Bibliometric analysis of the use of biochar in an environmental law perspective. *Journal of Engineering Science and Technology*, *19*, 167–176.

[17] Nandiyanto, A. B. D., Fiandini, M., Ragadhita, R., and Aziz, M. (2023). How to purify and experiment with dye adsorption using carbon: Step-by-step procedure from carbon conversion from agricultural biomass to concentration measurement using UV Vis spectroscopy. *Indonesian Journal of Science and Technology*, *8*(3), 363–380.

[18] Nandiyanto, A. B. D., Fiandini, M., Ragadhita, R., Maulani, H., Nurbaiti, M., Al-Obaidi, A.S.M., Yunas, J., and Bilad, M. R. (2023). Sustainable biochar carbon biosorbent based on tamarind (Tamarindus indica L) seed: Literature review, preparation, and adsorption isotherm. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *32*(1), 210–226.

[19] Nandiyanto, A. B. D., Fiandini, M., Fadiah, D. A., Muktakin, P.A., Ragadhita, R., Nugraha, W.C., Kurniawan, T., Bilad, M.R., Yunas, J., and Al Obaidi, A. S. M. (2023). Sustainable biochar carbon microparticles based on mangosteen peel as biosorbent for dye removal: Theoretical review, modelling, and adsorption isotherm characteristics. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *105*(1), 41–58.

[20] Nandiyanto, A. B. D., Fiandini, M., Ragadhita, R., Maryanti, R., Al Husaeni, D. F., and Al Husaeni, D. N. (2023). Removal of curcumin dyes from aqueous solutions using carbon microparticles from jackfruit seeds by batch adsorption experiment. *Journal of Engineering Science and Technology*, *18*(1), 653–670.

[21] Ramdhani, M. R., Kholik, A., Fauziah, R. S. P., Roestamy, M., Suherman, I., and Nandiyanto, A. B. D. (2023). A comprehensive study on biochar production, bibliometric analysis, and collaborative teaching practicum for Sustainable Development Goals (SDGs) in Islamic schools. *Jurnal Pendidikan Islam*, *9*(2), 123–144.

[22] Nandiyanto, A. B. D., Maryanti, R., Fiandini, M., Ragadhita, R., Usdiyana, D., Anggraeni, S., Arwa, W. R., and Al-Obaidi, A. S. M. (2020). Synthesis of carbon microparticles from red dragon fruit (Hylocereus undatus) peel waste and their adsorption isotherm characteristics. *Molekul*, *15*(3), 199–209.

[23] Campos, P., Miller, A. Z., Knicker, H., Costa-Pereira, M. F., Merino, A., and De La Rosa, J. M. (2020). Characteristics of biochar from various biomass. *Waste Management*, *105*, 256–266.

[24] Nandiyanto, A. B. D., Putri, A. R., Pratiwi, V. A., Ilhami, V. I. N., Kaniawati, I., Kurniawan, T., Farobie, O., and Bilad, M. R. (2024). Fourier transform infrared spectroscopy (FTIR)

of pyrolysis of polypropylene microparticles and its chemical reaction mechanism completed with computational bibliometric literature review to support sustainable development goals (SDGs). *Journal of Engineering, Science and Technology*, *19*(3), 1090-1104.

[25] Chen, M., Wang, D., Yang, F., Xu, X., Xu, N., and Cao, X. (2017). Biochar in environmental applications. *Environmental Pollution*, *230*, 540–549.

[26] Lonappan, L., Liu, Y. X., Rouissi, T., Brar, S. K., and Surampalli, R. Y. (2020). Nanobiochar synthesis and applications. *Journal of Cleaner Production*, *244*, 118841.

[27] Wang, D., Zhang, W., Hao, X., and Zhou, D. (2013). Micro- and nano-biochar transport. *Environmental Science and Technology*, *47*, 821–828.

[28] Pereira, P. H. F., Oliveira, L., Rosa, M. F., Cavalcanti, D. K. K., Moates, G. K., Wellner, N., Waldron, K. W., and Azeredo, H. M. C. (2016). Pomegranate peel composition and pyrolytic potential. *Industrial Crops and Products*, *88*, 68–75.

[29] Ragadhita, R., and Nandiyanto, A.B.D. (2023). Why 200°C is effective for creating carbon from organic waste (from thermal gravity (TG-DTA) perspective)?. *ASEAN Journal for Science and Engineering in Materials*, *2*(2), 75-80.

[30] Siddiqui, M. T. H., Sabzoi, N., Mujawar, M. N., Muhammad, A., Hussain, M., and Baloch, H. A. (2019). Yield of biochar from pomegranate peel. *Waste and Biomass Valorization*, *10*, 521–532.

[31] Ioannidi, A. A., Frigana, A., Vakros, J., Frontistis, Z., and Mantzavinos, D. (2024). Structural and functional transformation of biochar. *Catalysts*, *14*(127), 1–13.

[32] Liu, H., Zhu, J., Li, Q., Li, L., Huang, Y., Wang, Y., Fan, G., and Zhang, L. (2023). Functional groups in biochar. *Molecules*, *28*(2507), 1–14.

[33] Obinna, E.N. (2022). Physicochemical properties of human hair using Fourier Transform Infra-Red (FTIR) and Scanning Electron Microscope (SEM). *ASEAN Journal for Science and Engineering in Materials*, *1*(2), 71-74.

[34] Nandiyanto, A.B.D., Oktiani, R., and Ragadhita, R. (2019). How to read and interpret FTIR spectroscope of organic material. *Indonesian Journal of Science and Technology*, *4*(1), 97-118.

[35] Nandiyanto, A.B.D., Ragadhita, R., and Fiandini, M. (2023). Interpretation of Fourier Transform Infrared Spectra (FTIR): A practical approach in the polymer/plastic thermal decomposition. *Indonesian Journal of Science and Technology*, *8*(1), 113-126

[36] Fatimah, S., Ragadhita, R., Al Husaeni, D.F., and Nandiyanto, A.B.D. (2022). How to calculate crystallite size from x-ray diffraction (XRD) using scherrer method. *ASEAN Journal of Science and Engineering, 2*(1), 65-76.

[37] Sathyabama, K., and Firdous, S. (2025). Pyrolysis-induced structural evolution. *ACS Omega*, *10*, 37013–37024.

[38] Zhang, C., Chao, L., Zhang, Z., Zhang, L., Li, Q., Fan, H., Zhang, S., Liu, Q., Qiao, Y., Tian, Y., Wang, Y., and Hu, X. (2021). Thermal transition in biochar. *Renewable and Sustainable Energy Reviews*, *135*, 110416.

[39] Mu, B., Wang, H., Hao, X., and Wang, Q. (2018). XRD of lignocellulosic biomass biochar. *Polymers*, *10*(308), 1–12.

[40] Khater, E., Bahnasawy, A., Hamouda, R., Sabahy, A., Abbas, W., and Morsy, O. M. (2024). Mineral behavior during pyrolysis. *Scientific Reports*, *14*, 2625.

[41] Musa, N., Khan, K. S., Blankinship, J. C., Ijaz, S. S., Akram, Z., Alwahibi, M. S., Ali, M. A., and Yousra, M. (2024). Nutrient dynamics in manure-based biochar. *Sustainability*, *16*, 2755.

[42] Al-Sayed, H. M., Ali, A. M., Mohamed, M. A., and Ibrahim, M. F. (2022). Pyrolysis impact on electrical conductivity. *Journal of Soil Science and Plant Nutrition*, *22*, 3541–3552.

[43] Ragadhita, R., Fiandini, M., Al Husaeni, D.N., and Nandiyanto, A.B.D. (2026). Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches. *Indonesian Journal of Science and Technology*, *11*(1), 1-26.

[44] Basnur, J., Putra, M.F.F., Jayusman, S.V.A., and Zulhilmi, Z. (2024). Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *3*(1), 51-58.

[45] Sesrita, A., Adri, H.T., Suherman, I., Rasmitadila, R., and Fanani, M.Z. (2025). Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting sustainable development goals (SDGs): A techno-economic and bibliometric analysis. *ASEAN Journal for Science and Engineering in Materials*, *4*(2), 245-266.

[46] Henny, H., Budi, A.H.S., Andriyansyah, M., Ar Rozzak, M.R., Baru, M.M., and Masek, A. (2025). Hazard identification, risk assessment, and determining control (HIRADC) for workplace safety in manufacturing industry: A risk-control framework complete with bibliometric literature review analysis to support sustainable development goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *4*(2), 267-284.

[47] Syahrudin, D., Roestamy, M., Fauziah, R.S.P., Rahmawati, R., Pratidina, G., Purnamasari, I., Muhtar, S., and Salbiah, E. (2026). Techno-economic analysis of production ecobrick from plastic waste to support sustainable development goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *5*(1), 9-16.

[48] Apriliani, A., Waahyudin, C., Ramdani, F.T., Martin, A.Y., Syahrudin, D., Hernawan, D., and Salbiah, E. (2026). Techno-economic analysis of sawdust-based trash cans and their contribution to Indonesia’s green tourism policy and the Sustainable Development Goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *5*(1), 17-36.

[49] Ragadhita, R., Nandiyanto, A.B.D., Farobie, O., Kurniawan, T., and Bilad, M.R. (2026). Definition and role of sustainable materials in reaching global Sustainable Development Goals (SDGs) completed with bibliometric analysis. *ASEAN Journal for Science and Engineering in Materials*, *5*(1), 53-100.

[50] Al-Obaidi, A.S.M. (2026). The Journal of Engineering, Science and Technology (JESTEC): A bibliometric insight into materials research trends and innovation to support Sustainable Development Goals (SDGs). *ASEAN Journal for Science and Engineering in Materials*, *5*(1), 101-122.

[51] Xing, G., Chano, J., Thadanatthaphak, Y., and Wu, C.C. (2025). Physical adaptation of college students in high-altitude training: Empirical findings and curriculum development insights to support Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(2), 215-236.

[52] Imaniyati, N., Ratnasari, C.D., and Adman, A. (2025). Enhancing job satisfaction through human resource information systems and communication: A commitment-based

approach to achieve Sustainable Development Goals (SDGs) in education-oriented organizations. *ASEAN Journal of Educational Research and Technology*, *4*(2), 237-254.

[53] Di, R., Sawangboon, T., and Chano, J. (2025). Enhancing innovative thinking through a theory-based instructional model in design education to support Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(3), 311-332.

[54] Wiyanarti, E., and Nurjannah, A.N. (2026). Influence of self-efficacy on affective learning outcomes in social studies education toward achieving Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(1), 1-18.

[55] Yu, X., Chano, J., and Wongsaphan, M. (2026). Enhancing occupational identity and self-efficacy through a self-education model in art and design education aligned with Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(1), 19-46.

[56] Nurjamin, A., Nurjamin, L.R., Fajriah, Y.N., Nurjamin, A.K., and Firdaus, H.A. (2026). Integrating generative artificial intelligence (AI)-based multimodal learning in education to enhance literacy aligned with Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(1), 71-88.

[57] Abduh, A., Achmad, S.F., Syam, C., Samad, S., Arham, M., Mustafa, M., and Pandang, A. (2026). Dataset on the number of schools, teachers, and students in Sulawesi, Indonesia: kindergarten, primary, junior, senior high, vocational, and Islamic boarding schools with educational access, quality, and cultural implications to solve challenges and strategies in education management and support Sustainable Development Goals (SDGs). *ASEAN Journal of Educational Research and Technology*, *4*(1), 89-116.

[58] Khamdamovna, K.S. (2025). Enhancing professional readiness in vocational education through an integrative approach aligned with the Sustainable Development Goals (SDGs). *ASEAN Journal for Science Education*, *4*(2), 143-154

[59] Ximenes, S.M. (2025). School feeding program and Sustainable Development Goals (SDGs) in education: Linking food security to learning outcomes in Timor-Leste. *ASEAN Journal for Science Education*, *4*(2), 155-168

[60] Haq, M.R.I., Nurhaliza, D.V., Rahmat, L.N., and Ruchiat, R.N.A. (2024). The influence of environmentally friendly packaging on consumer interest in implementing zero waste in the food industry to meet sustainable development goals (SDGs) needs. *ASEAN Journal of Economic and Economic Education*, *3*(2), 111-116.

[61] Maulana, I., Asran, M.A., and Ash-Habi, R.M. (2023). Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste. *ASEAN Journal of Community Service and Education*, *2*(2), 141-146.

[62] Nurnabila, A.T., Basnur, J., Rismayani, R., Ramadhani, S., and Zulhilmi, Z. (2023). Analysis of the application of mediterranean diet patterns on sustainability to support the achievement of sustainable development goals (SDGs): Zero hunger, good health and well beings, responsible consumption, and production. *ASEAN Journal of Agricultural and Food Engineering*, *2*(2), 105-112.

[63] Awalussillmi, I., Febriyana, K.R., Padilah, N., and Saadah, N.A. (2023). Efforts to improve sustainable development goals (SDGs) through education on diversification of food

using infographic: Animal and vegetable protein. *ASEAN Journal of Agricultural and Food Engineering*, *2*(2), 113-120.

[64] Rahmah, F.A., Nurlaela, N., Anugrah, R., and Putri, Y.A.R. (2024). Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health. *ASEAN Journal of Agricultural and Food Engineering*, *3*(1), 57-66.

[65] Keisyafa, A., Sunarya, D.N., Aghniya, S.M., and Maula, S.P. (2024). Analysis of student's awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030. *ASEAN Journal of Agricultural and Food Engineering*, *3*(1), 67-74.