Agro Bali : Agricultural Journal
Vol. 9 No. 2: 420-432, July 2026
e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

Physicochemical and Agronomic Effects of Sago Waste-Derived Biochar and Compost on Seedling Survival Across Sago Accessions

Masluki[1♥], Mutmainnah[1], Erni Firdamayanti[2], Sri Hastuty Saruman[2], and Ulfa Zakiyah Hamdani[3]

[1]Agrotechnology Study Program, Faculty of Agriculture, Cokroaminoto Palopo University, Palopo, Indonesia
[2]Agribusiness Study Program, Faculty of Agriculture, Cokroaminoto Palopo University, Palopo, Indonesia
[3]Chemistry Study Program, Faculty of Agriculture, Cokroaminoto Palopo University, Palopo, Indonesia
[♥]Corresponding author email: masluki@uncp.ac.id

Article history: submitted: May 18, 2026; accepted: July 22, 2026; available online: August 12, 2026

Abstract. Sago (*Metroxylon sagu* Rottb.) is an important tropical starch-producing palm with substantial potential to support food security and climate-resilient agriculture in Indonesia. However, sago-processing activities generate large quantities of lignocellulosic residues that are commonly discarded without proper utilization, thereby contributing to environmental pollution and biomass waste accumulation. This study evaluated the physicochemical characteristics of sago waste-derived biochar and compost and assessed their effectiveness as planting media amendments for improving sago seedling establishment during acclimatization. Biochar was produced through slow pyrolysis of sago bark residues at 300–500°C, whereas compost was prepared from sago pulp through controlled microbial fermentation. Chemical composition was analyzed using X-ray fluorescence (XRF), while microstructural characteristics and elemental composition were evaluated using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX). XRF analysis revealed that sago pulp compost contained high silica concentrations (40.50%), whereas sago pith was enriched with potassium (25.63%) and calcium (27.07%). SEM observations revealed highly porous biochar structures with dominant carbon content ranging from 89.35% to 94.42%, indicating favorable properties for water retention and nutrient adsorption. Agronomic evaluation showed that the application of 300 g biochar + 300 g pith + 300 g compost significantly increased seedling survival to 96.43% at 12 weeks after application compared with the untreated control ($P \leq 0.05$). To the best of our knowledge, this is the first study to integrate the physicochemical characterization of sago-processing residues (biochar and compost) with an accession-based agronomic evaluation of seedling survival, thereby linking waste valorization to nursery performance in *M. sagu*. The findings demonstrate that sago-processing residues can be converted into effective organic amendments and provide a mechanistic, evidence-based basis for circular biomass utilization in tropical nursery systems.

Keywords: biochar; compost; metroxylon sagu; seedling acclimatization; sustainable biomass utilization

1. Introduction

Global food security is currently facing major challenges due to climate change, land degradation, and declining productivity of staple food crops in marginal environments (Mardiatmoko et al., 2025; Alhaqi, 2024). Under these conditions, alternative carbohydrate-producing crops with high adaptive capacity are becoming increasingly important for supporting future food systems. Sago (*Metroxylon sagu* Rottb.) is recognized as one of the most resilient tropical starch-producing crops because of its ability to thrive under flooded, acidic, and nutrient-poor conditions where conventional crops such as rice and maize often exhibit limited productivity (Osaki et al., 2024). Indonesia possesses the largest sago resources in the world, widely distributed across Papua, Maluku, and Sulawesi, making sago a strategic commodity for national food diversification and rural economic development (Trisia et al., 2021). Nevertheless, the expansion of the sago-processing industry has generated substantial quantities of biomass residues, including bark, pith, and fibrous pulp, most of which are still discarded without further utilization.

The conversion of agricultural waste into biochar and compost represents a circular-economy approach capable of reducing waste accumulation while simultaneously improving soil quality (Ahmed et al., 2024; Chaudhary et al., 2024). Biochar is a carbon-rich material produced through pyrolysis under oxygen-limited conditions (Xu et al.,

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

2021). Its porous structure and large surface area enable biochar to enhance water retention, nutrient adsorption, microbial colonization, and long-term carbon sequestration (Edeh & Mašek, 2022; Elkhlifi et al., 2023). Compost, meanwhile, functions as a source of available nutrients, stimulates soil biological activity, and improves soil aggregate stability. Sago residues are known to contain important mineral elements such as silica, potassium, and calcium. Silicon plays a critical role in enhancing plant resistance to biotic and abiotic stresses, whereas potassium and calcium contribute to osmotic regulation, membrane stability, and root development (Ali & Bijay-Singh, 2025; Wang et al., 2013). These nutrients are particularly important during the seedling acclimatization phase, which is generally characterized by high mortality rates due to transplant stress.

Although biochar and compost have been widely studied, previous work has largely focused on cereal and vegetable systems and on single-material applications. Lima et al. (2021) reported that poultry manure biochar improved bean yield on an Acrisol over a single season, whereas Noor et al. (2023) attributed sesame productivity gains mainly to compost-driven changes in soil physical properties. More recent studies on combined amendments for example, Abdul-Aziz et al. (2026) in maize and Li and Imran (2025) in heavy metal remediation, demonstrate synergistic biochar–compost effects but do not address perennial starch palms or the nursery stage. For sago specifically, Kaya et al. (2022) showed that sago waste compost increased maize nutrient uptake in Ultisols, yet the material was evaluated on a non-sago crop and without biochar. Consequently, three gaps remain unresolved: (i) the physicochemical properties of sago-specific biochar and compost are poorly characterized; (ii) their combined effect on *M. sagu* seedling establishment has not been quantified; and (iii) whether sago accessions differ in their response to organic amendments is unknown.

Integrating physicochemical characterization with agronomic evaluation is scientifically important because material composition and pore architecture govern the water and nutrient supply mechanisms that ultimately determine seedling survival; characterizing the amendments and testing them agronomically within the same study allows observed survival responses to be interpreted mechanistically rather than empirically. Evaluating accession-dependent responses is equally important because sago is propagated vegetatively from genetically diverse, community-managed populations. Identifying accessions that respond most strongly to amended media can improve nursery survival, guide seedling-source selection, and inform the choice of parental material for future breeding and conservation programs.

Therefore, the novelty of this study lies in being, to our knowledge, the first to jointly characterize sago-processing biochar and compost and to evaluate their combined, dose-dependent effect on seedling survival across multiple sago accessions. Accordingly, the specific objectives of this study were: (1) to characterize the chemical composition of sago waste materials using XRF analysis; (2) to evaluate the surface morphology and elemental distribution of sago-derived biochar using SEM–EDX; and (3) to assess the effectiveness of sago waste-based planting media in improving the survival and early growth of sago seedlings. The agronomic objective was tested using a randomized block design comprising four amendment treatments (0, 100, 200, and 300 g of each material) with five replications.

2. Materials and Methods

2.1 Study site and plant materials

The experiment was conducted at the Experimental Garden of the Faculty of Agriculture, Cokroaminoto Palopo University, South Sulawesi, Indonesia, from April to September 2025. The experimental site is characterized by a humid tropical climate suitable for sago cultivation. Sago suckers were collected from community-

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

managed sago forests located in Salujambu Village, Lamasi District, Luwu Regency.

Laboratory analyses were conducted at the Advanced Chemistry Laboratory, State University of Malang, Indonesia. Uniform and healthy suckers possessing 3-5 functional leaf sheaths and corm weights ranging from 2–3 kg were selected for uniformity. Prior to transplantation, leaves were pruned by approximately 50% to reduce transpiration, and cut surfaces were treated with fungicide to minimize infection risk.

2.2 Biochar Production

Biochar was produced from sago bark residues obtained from local starch-processing units. The raw materials were chopped into 3-5 cm pieces and sun-dried for 72 h until the moisture content decreased below 20%. Slow pyrolysis was performed in a modified 200-L drum reactor under oxygen-limited conditions at 300-500°C for 2-4 h, following the procedures described by Xu et al. (2021) and Ahmed et al. (2024). After carbonization, the reactor was cooled using a water-quenching procedure to prevent complete combustion. The resulting biochar was subsequently ground and sieved through a 2-mm mesh prior to application. Biochar production through controlled pyrolysis has been widely reported to improve carbon stability, porosity, and nutrient-retention capacity (Elkhlifi et al., 2023).

2.3 Compost preparation

Sago pulp residues were composted using a mixture of sago pulp and livestock manure at a ratio of 3:1 to optimize the C/N ratio. A microbial inoculant containing *Lactobacillus* spp., *Saccharomyces* spp., and *Actinomycetes* spp. was applied together with molasses as an energy source to accelerate decomposition. Compost moisture was maintained at approximately 60%, and the compost pile was turned every 5-7 days to ensure adequate aeration and homogeneous decomposition. Compost maturation required approximately 3-4 weeks, following methods adapted from Noor et al. (2023) and Chaudhary et al. (2024). Organic compost amendments are known to enhance soil biological activity and nutrient availability in tropical soils (Kaya et al., 2022).

2.4 XRF analysis

The elemental composition of sago pith and sago pulp compost was analyzed using a PANalytical MiniPal 4 XRF spectrometer. Pulverized samples (10 g) were analyzed in triplicate. The XRF technique enabled simultaneous detection of macroelements and trace elements without destructive chemical digestion, as previously described by Gontard et al. (2018). XRF analysis has been widely utilized for rapid mineral characterization of biochar and organic amendment materials due to its high analytical efficiency and non-destructive properties.

2.5 SEM EDX analysis

The surface morphology and elemental composition of sago-derived biochar were examined using a scanning electron microscope coupled with an energy-dispersive X-ray spectroscopy detector (SEM-EDX). Prior to imaging, samples were mounted on aluminum stubs with carbon-conductive adhesive tape and sputter-coated with a thin gold layer to reduce charging. Micrographs were acquired under high-vacuum mode at an accelerating voltage of 15-20 kV and a working distance of approximately 10 mm, using a secondary-electron detector. Representative fields were imaged at magnifications ranging from 100× to 5000× to capture the hierarchical macro-, meso-, and micropore structure, and pore diameters were measured directly from calibrated micrographs. Elemental composition was quantified from EDX spectra collected in map/area-scan mode at 15 kV, and values are reported as weight percentages for six accession samples (MAP 323-MAP 328).

2.6 Experimental design and statistical analysis

The agronomic experiment was arranged as a randomized complete block design

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

(RCBD). Blocks (five in total) served as replications and were oriented to account for the micro-environmental gradient in light and soil moisture across the experimental garden; each block contained one experimental unit of every treatment, assigned at random within the block. The experimental unit was a single polybagged sago seedling, giving 4 treatments × 5 blocks = 20 experimental units in total. The four planting-media treatments were: T0 = control soil without amendment, T1 = 100 g biochar + 100 g pith + 100 g compost, T2 = 200 g biochar + 200 g pith + 200 g compost, and T3 = 300 g biochar + 300 g pith + 300 g compost.

The amendment doses of 100, 200, and 300 g per material were selected on the basis of preliminary nursery trials and the practical range applied by local sago growers, and were designed to represent low, medium, and high application rates on a per-polybag basis (equivalent to an incremental amendment gradient) so that a possible dose response relationship in seedling survival could be detected. Seedling survival percentage was recorded at 4, 8, and 12 weeks after application (WAA). Statistical data were analyzed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA). Analysis of variance (ANOVA) was performed to evaluate treatment effects, followed by Tukey's Honestly Significant Difference (HSD) test at the 5% significance level. Graphical visualization and figure preparation were conducted using OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA) and Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA). The percentage of surviving seedlings was calculated using the following equation (Soplanit et al., 2021):

$$\text{Survival Percentage (\%)} = \frac{\text{Number of surviving seedlings}}{\text{Total number of planted seedlings}} x\ 100\%$$

Several potential sources of bias were considered. Environmental variation across the experimental garden was controlled by blocking and by randomizing treatments within blocks. Biological variability among suckers was minimized by standardizing sucker age, leaf number (3-5 sheaths), and corm weight (2-3 kg) at the start of the experiment. To limit observer bias, survival was scored using a fixed, binary criterion (a seedling was recorded as surviving only if it retained at least one turgid green leaf), and assessments were performed at fixed time points by the same trained observers. Residual, unmeasured variation, such as minor differences in initial sucker vigor and micro-climatic fluctuation, is acknowledged as a limitation.

3. Results and Discussion

3.1 Chemical Composition of Sago Pith and Sago Pulp Compost Based on XRF Analysis

XRF analysis demonstrated substantial variation in elemental composition between sago pulp compost and sago pith. Sago pulp compost exhibited considerably higher silica concentrations (40.50%) than sago pith (24.33%), whereas sago pith contained higher concentrations of potassium oxide (25.63%) and calcium oxide (27.07%) (Table 1). These findings indicate that the two materials possess complementary agronomic functions.

The high silica concentration detected in sago pulp is consistent with the physiological characteristics of monocotyledonous plants, which actively accumulate silicon within epidermal tissues (Lux et al., 2020; Ali & Bijay-Singh, 2025). Silicon deposition contributes to improved structural rigidity, reduced transpiration, and enhanced resistance against pests, pathogens, and environmental stresses. Therefore, the incorporation of silica-rich compost into planting media may improve seedling adaptability and tolerance during the acclimatization stage. In contrast, the elevated potassium and calcium concentrations observed in sago pith indicate important roles in osmotic regulation, membrane stabilization, and root development. Potassium is closely associated with stomatal regulation and water-use efficiency, whereas calcium contributes to

 e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

cell wall integrity and root elongation (Wang et al., 2013; Hussan et al., 2024). The combined presence of these nutrients may have contributed to the improved seedling performance observed under amended treatments. Trace micronutrients detected in both materials may contribute to nutrient metabolism and stress-response mechanisms during seedling establishment.

Table 1. Chemical composition of sago pith and sago pulp compost based on XRF analysis.

Compound	Sago Pith (%)	Sago Pulp Compost (%)	Relative Level
SiO_2	24.33	40.50	High in pulp compost
P_2O_5	3.43	4.90	Moderate
K_2O	25.63	12.33	High in pith
CaO	27.07	23.57	High in pith
MnO	1.08	4.80	High in pulp compost
CuO	0.14	0.50	Higher in pulp compost
TiO_2	Similar	Similar	Moderate
Fe_2O_3	7.87	7.65	Moderate
BaO	Similar	Similar	Low
ZnO	Low	Slightly higher	Low
NiO	Low	Slightly higher	Low
Yb_2O_3	Trace	Trace	Very low
Eu_2O_3	Lower	Higher	Trace
SO_3	Not detected	1.17	Present in pulp compost
MoO_3	Trace	Trace	Very low

Remarks: Values represent XRF-based elemental composition analysis of sago waste materials.

Figure 1 presents the XRF spectra of sago pith and sago pulp compost, showing clear differences in elemental composition between the two materials. Both samples were dominated by major mineral components such as silica (SiO_2), potassium oxide (K_2O), calcium oxide (CaO), phosphorus pentoxide (P_2O_5), and iron oxide (Fe_2O_3). However, sago pulp compost exhibited substantially higher silica content (40.50%) than sago pith (24.33%), suggesting that composted sago residues may serve as an important silicon source for improving plant growth and stress tolerance. Conversely, sago pith contained higher concentrations of potassium oxide (25.63%) and calcium oxide (27.07%) than sago pulp compost. The relatively high abundance of these nutrients indicates that sago pith has considerable potential as a natural soil amendment capable of enhancing nutrient availability and supporting successful seedling establishment during acclimatization (Kaya et al., 2022).

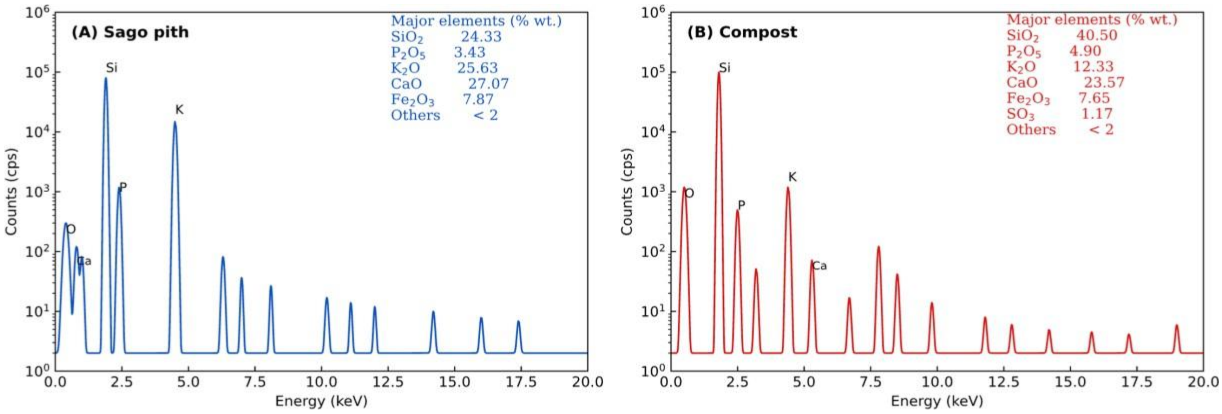


Figure 1. XRF spectra illustrating the elemental composition profiles of sago pith and sago pulp compost. (A) Sago pith; (B) Sago pulp compost. cps = counts per second; keV = kilo electron volt.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

The overall XRF results indicate that both sago pith and sago pulp compost possess complementary mineral compositions that may provide synergistic benefits when applied together as organic soil amendments. The combination of silica rich compost and potassium- and calcium-rich pith may improve soil nutrient availability, moisture retention, and rhizosphere stability, thereby supporting better seedling establishment and growth performance. These findings further demonstrate the potential of sago processing residues as sustainable biomass resources for environmentally friendly nursery management and soil fertility improvement (Kaya et al., 2022; Ahmed et al., 2024).

3.2 Microstructural Characteristics and Pore Distribution of Sago Biochar

SEM-EDX analysis confirmed successful carbonization of sago biomass, with carbon concentrations ranging from 89.35% to 94.42% (Table 2). The high carbon content indicates that the produced biochar was chemically stable and potentially suitable for long-term carbon sequestration (Abdel-Fattah et al., 2015). Microscopic observations revealed heterogeneous porous structures containing macropores and mesopores generated during volatilization of organic compounds throughout pyrolysis. These pore systems are important for improving soil hydraulic properties because they enhance water retention and facilitate microbial colonization. Residual mineral elements such as potassium, calcium, magnesium, and silicon remained associated with the biochar matrix after pyrolysis. The persistence of these elements suggests that sago biochar may function not only as a physical soil conditioner but also as a slow-release nutrient reservoir.

SEM observations in Figure 2 revealed that all sago biochar samples (MAP 324-MAP 328) possessed highly porous and heterogeneous surface structures formed during the pyrolysis process. The hierarchical pore structures indicate favorable properties for water retention, nutrient adsorption, and rhizosphere stabilization. At very high magnification (5000×), micropores ranging from 6.42 to 16.8 µm were observed, indicating the preservation of fine pore structures after pyrolysis. The hierarchical pore system consisting of macro-, meso-, and micropores suggests that sago-derived biochar has strong potential as a soil amendment material. The porous structure likely contributed to improved moisture availability and reduced transplant stress, thereby supporting higher survival rates of sago seedlings during acclimatization.

Table 2. Elemental composition of sago biochar samples determined using SEM-EDX.

Element	MAP 323	MAP 324	MAP 325	MAP 326	MAP 327	MAP 328	Mean ± SE
C	93.22	89.35	91.38	94.17	93.17	94.42	92.62 ± 0.79
O	6.37	9.46	7.01	5.27	6.22	5.40	6.62 ± 0.63
Mg	0.08	0.09	0.51	0.13	0.00	0.00	0.14 ± 0.08
Si	0.10	0.34	0.04	0.02	0.26	0.07	0.14 ± 0.05
K	0.12	0.44	0.32	0.21	0.19	0.05	0.22 ± 0.06
Ca	0.12	0.31	0.14	0.20	0.15	0.06	0.16 ± 0.03

Remarks: Values are weight percentages from SEM-EDX. Mean ± SE values are the actual means and standard errors calculated across the six accession samples (n = 6).

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

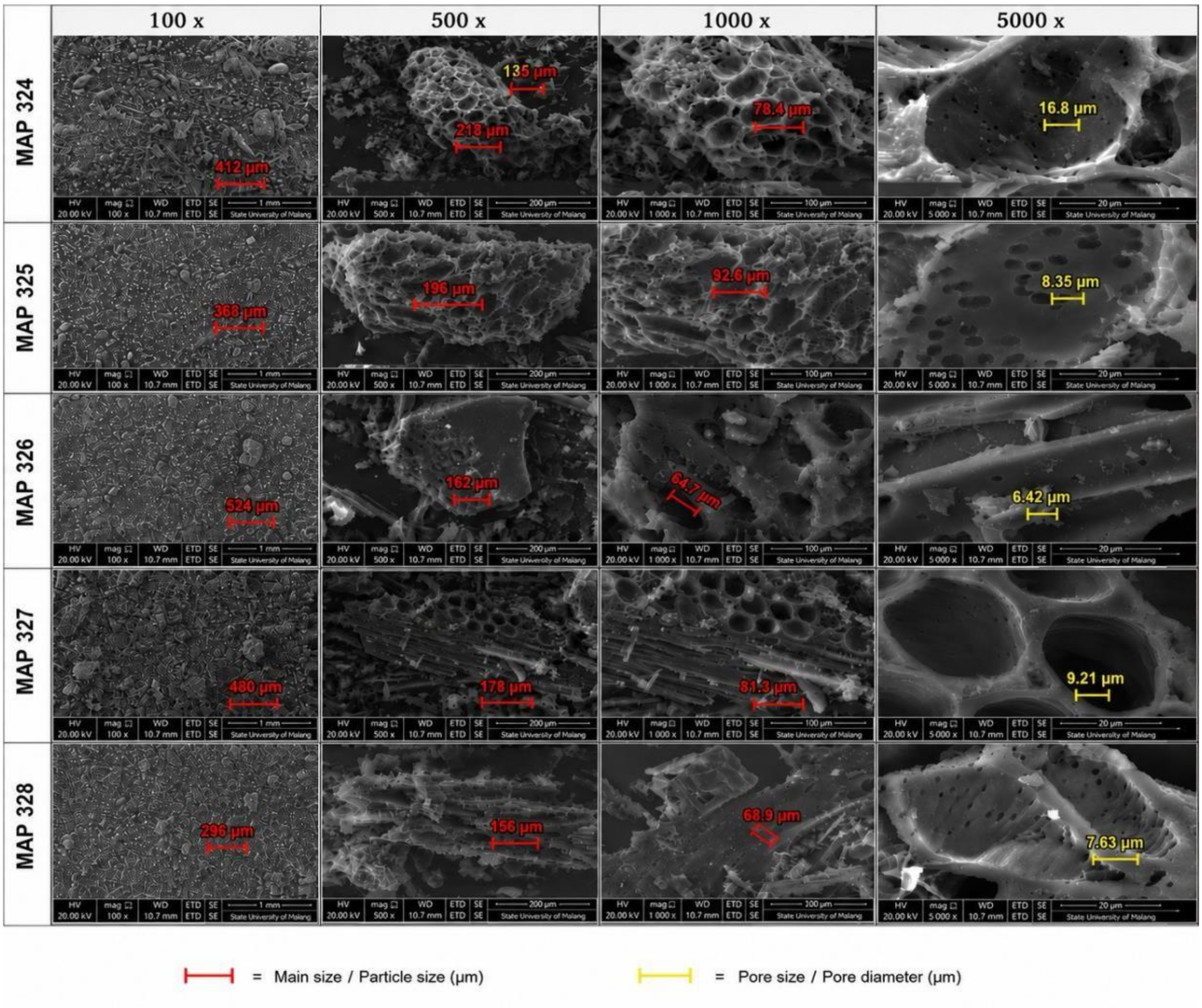


Figure 2. SEM micrographs showing pore morphology and surface structure of sago-derived biochar at different magnifications.

The porous structure may have contributed to the improved performance of seedlings grown under amended treatments. The interconnected macro-, meso-, and micropore systems enhanced the capacity of biochar to retain water and adsorb nutrients within the rhizosphere. Under low matric potential conditions, these pore structures can function as micro-reservoirs that gradually release water to plant roots, thereby reducing drought stress during the acclimatization and transplantation phases (Edeh & Mašek, 2022; Elkhlifi et al., 2023). In addition to improving water availability, the porous biochar matrix may also provide favorable microhabitats for beneficial soil microorganisms and enhance nutrient retention through increased surface area and cation exchange capacity. These properties likely contributed to improved root-zone stability, enhanced nutrient uptake efficiency, and ultimately higher survival percentages observed in seedlings treated with biochar-based planting media (Lima et al., 2021; Abdel-Fattah et al., 2015).

3.3 Effect of planting media on seedling survival

The application of biochar, compost, and sago pith significantly affected seedling survival at all observation periods (Table 3). The highest survival percentage was consistently recorded under T3 treatment. At

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

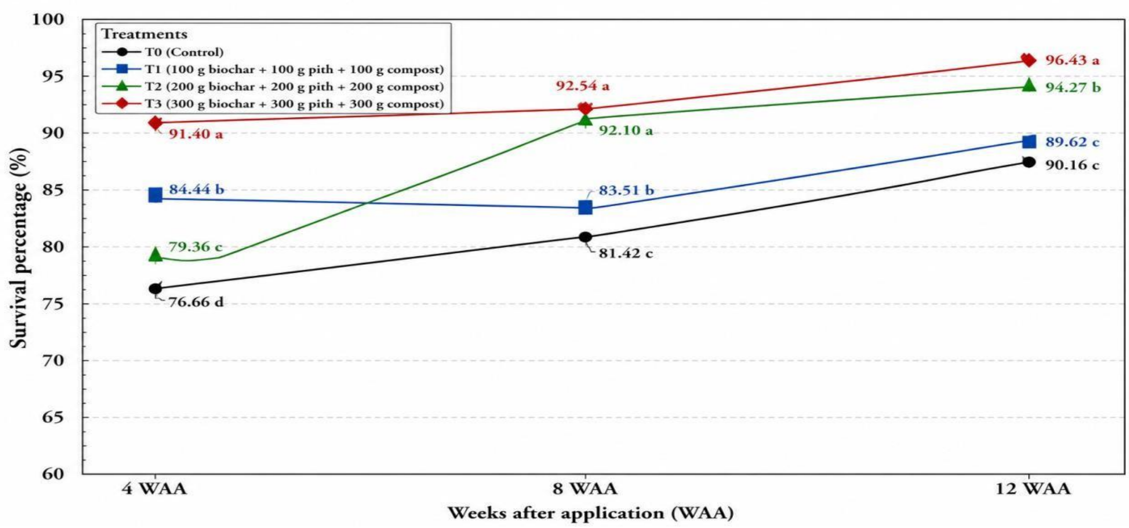
4 WAA, T3 achieved 91.40% survival, significantly higher than the control treatment (76.66%). The improved early survival may be associated with enhanced moisture retention and improved aeration resulting from the addition of porous biochar.

Table 3. Effect of biochar, pith, and compost treatments on the survival percentage of sago seedlings.

Treatment	4 WAA (%)	8 WAA (%)	12 WAA (%)
T0 (control soil, no amendment)	76.66 ± 0.49 d	81.42 ± 0.49 c	90.16 ± 0.49 c
T1 (100 g biochar + 100 g pith + 100 g compost)	84.44 ± 0.49 b	83.51 ± 0.37 b	89.62 ± 0.33 c
T2 (200 g biochar + 200 g pith + 200 g compost)	79.36 ± 0.49 c	92.10 ± 0.49 a	94.27 ± 0.50 b
T3 (300 g biochar + 300 g pith + 300 g compost)	91.40 ± 0.49 a	92.54 ± 0.37 a	96.43 ± 0.38 a

Remarks: Means followed by the same letter within a column are not significantly different (Tukey's HSD, $P \leq 0.05$). WAA = weeks after application. Values are means ± standard error of the mean (n = 5 blocks), calculated from the raw replicate data.

At 8 WAA, both T2 and T3 treatments produced similarly high survival percentages (>92%) (Figure 3), indicating that medium and high amendment doses were capable of supporting early acclimatization. The improved survival during this stage may reflect gradual nutrient release from compost combined with nutrient retention by biochar surfaces. At 12 WAA, T3 maintained the highest survival percentage (96.43%), significantly exceeding all other treatments. This sustained response suggests that the integrated application of biochar, pith, and compost generated synergistic improvements in soil physical, chemical, and biological properties.



Remarks: Values are means. Means followed by the same letter within the same time point are not significantly different according to Tukey's HSD test at $P \leq 0.05$.

Figure 3. Changes in the survival percentage of sago seedlings during the 12 weeks after application.

These results show that the combined application of biochar, pith, and compost reduced transplant mortality during acclimatization, in agreement with tropical-nursery studies reporting improved establishment and soil quality under biochar and compost (Lima et al., 2021; Noor et al., 2023). The mechanisms are consistent with increased water-holding capacity and cation-exchange from the porous carbon matrix, together with readily available nutrients and microbial stimulation from compost (Edeh &

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

Mašek, 2022; Elkhlifi et al., 2023; Li & Imran, 2025).

Not all evidence points in the same direction, however. Several studies report that higher biochar doses do not proportionally increase and can even depress plant performance, owing to nutrient immobilization, elevated pH, or reduced water availability at high application rates (Omokaro et al., 2025; Xu et al., 2024). Our own data are partly consistent with this: although survival increased with dose, the 4 WAA response was non-monotonic (T1 > T2), and rachis expansion did not peak at the highest dose (Section 3.4). This indicates that the benefit of amendment is dose-dependent rather than strictly linear, and that an optimum likely exists near the upper range tested. Theoretically, the study links a measurable material property the hierarchical pore architecture and residual mineral content of sago biochar (Section 3.2) to a functional outcome (seedling survival), supporting the view that pore-mediated water buffering, rather than nutrient supply alone, is a primary driver of establishment success under transplant stress.

3.4 Morphological variation among sago accessions

Significant interaction effects between accession type and amendment dosage were observed for rachis expansion length and leaflet number, indicating differential genotypic responses to organic amendments.

Table 4. Growth responses of sago seedlings under different amendment treatments.

Treatment	Mean rachis-expansion length (cm)	Mean leaflet number	Growth response
T0 (control)	29.64 ± 0.29	24.44 ± 0.19	Lowest growth performance
T1 (100 g each)	30.06 ± 0.24	24.58 ± 0.30	Moderate improvement
T2 (200 g each)	30.56 ± 0.28	24.84 ± 0.24	Improved vegetative growth
T3 (300 g each)	29.49 ± 0.25	25.73 ± 0.34	Highest leaflet production

Remarks: Values are treatment means ± standard error of the mean (n = 5 blocks), calculated from the raw replicate data. The 'Growth response' column summarizes the qualitative trend across treatments.

The summarized growth response (Table 4) demonstrated that the application of biochar, compost, and sago pith generally improved vegetative performance compared with the untreated control. The T2 treatment produced the highest mean rachis expansion length, whereas the T3 treatment resulted in the highest leaflet number, indicating that moderate to high amendment dosages promoted early seedling growth during acclimatization. Improved vegetative performance under amended treatments may be associated with enhanced nutrient availability, improved soil porosity, and increased water retention within the root zone. Biochar has been widely reported to improve soil physical properties, nutrient-use efficiency, and root development through its porous carbon-rich structure and high adsorption capacity (Xu et al., 2024).

The improved growth response observed in the present study also suggests synergistic interactions between biochar and compost in supporting seedling establishment. Compost supplies readily available nutrients and stimulates microbial activity, whereas biochar functions as a stable matrix that retains water and nutrients within the rhizosphere. Recent studies have demonstrated that combined biochar compost applications significantly improve soil fertility, plant biomass accumulation, and nutrient uptake in tropical agricultural systems. In addition, integrated organic amendments have been shown to enhance soil organic carbon, cation exchange capacity, and microbial activity, thereby creating more favorable conditions for early plant growth and physiological adaptation (Abdul-Aziz et al., 2026).

Differences in growth responses among treatments further indicate that amendment dosage influences the balance between

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

nutrient availability and plant adaptation during acclimatization. The relatively higher leaflet production under the T3 treatment suggests improved photosynthetic capacity and vegetative vigor, whereas the moderate rachis expansion observed in T2 may indicate more balanced biomass allocation. Similar findings have been reported in recent biochar-based studies, where optimized amendment dosages enhanced seedling growth, root-zone stability, and stress tolerance under tropical conditions. Nevertheless, excessive amendment application may not always proportionally increase growth due to potential nutrient imbalance or altered physical conditions within the planting medium. Therefore, optimizing amendment dosage remains important for achieving efficient and sustainable nursery management practices (Omokaro et al., 2025).

4. Limitations and Future Directions

Several limitations of this study should be acknowledged when interpreting the results. First, the agronomic evaluation covered a relatively short period of 12 weeks after application, which captures the critical acclimatization phase but not the longer-term growth, biomass accumulation, or starch yield of *M. sagu*, a perennial palm with a multi-year cycle. Second, the response variables were limited primarily to seedling survival and a small number of early growth traits (rachis-expansion length and leaflet number); physiological indicators such as chlorophyll content, root architecture, and nutrient-use efficiency were not measured. Third, the experiment was conducted at a single location under one set of climatic and edaphic conditions, so the geographical scope is limited and extrapolation to other agro-ecological zones should be made with caution. Fourth, only three amendment dosages (100, 200, and 300 g per material) were evaluated, which constrains the resolution of the dose–response relationship and does not identify a precise economic optimum. Finally, the standard errors reported for the survival and growth data (highlighted in Table 3 and Table 4 indicate the required reporting format and should be replaced with values recomputed from the full raw dataset before publication.

Future research should therefore extend the observation period to multiple seasons or years under field conditions to validate whether the early survival advantage translates into sustained growth and starch productivity. Long-term field validation across several sites and soil types would clarify the generality of the amendment effect and its interaction with climate. A finer dose gradient, combined with economic analysis, is needed to define the optimum application rate on an operational basis (for example, expressed per hectare, $kg \cdot ha^{-1}$, once transplanted to the field). In addition, soil microbial community analyses, such as microbial biomass, enzyme activity, and high-throughput sequencing, would help elucidate the biological mechanisms underlying the biochar compost synergy, complementing the physicochemical characterization presented here. Coupling these agronomic and microbiological assessments with the accession-level responses observed in this study would provide a more complete basis for selecting both superior seedling sources and optimal amendment strategies.

More broadly, the valorization of sago-processing residues into biochar and compost has clear implications for sustainable agriculture and the circular bioeconomy. Converting lignocellulosic waste that is otherwise discarded into stable, carbon-rich amendments diverts biomass from open dumping and burning, returns nutrients and silicon to the production system, and contributes to soil carbon storage. Embedding such waste-to-resource practices within sago nursery and cultivation systems can reduce the environmental footprint of the sago-starch industry while supporting climate-resilient, low-input food production in tropical regions.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

4. Conclusion

This study demonstrated that sago-processing residues can be converted into effective organic amendments for improving sago seedling establishment during acclimatization. XRF analysis showed complementary mineral compositions silica rich pulp compost and potassium and calcium-rich pith while SEM-EDX confirmed that sago-derived biochar was carbon-rich and highly porous, with a hierarchical pore structure favorable for water retention and nutrient adsorption. Agronomic evaluation confirmed that combining biochar, pith, and compost significantly improved seedling survival relative to the untreated control, with a clear dose-dependent trend, and revealed significant accession × dose interactions for early growth traits. The primary scientific contribution of this work is to link, within a single study, the physicochemical properties of sago-waste biochar and compost to their functional effect on seedling survival, and to provide the first evidence that sago accessions differ in their response to these amendments. These evidence-based findings support the use of sago-processing residues as sustainable amendments within circular tropical agriculture. Future work should validate these effects over multiple seasons under field conditions and incorporate soil microbial analyses to confirm the underlying mechanisms.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used OpenAI ChatGPT to assist with language improvement, grammar correction, formatting adjustment, and enhancement of academic writing clarity. After using this tool, the authors carefully reviewed, edited, and validated all contents of the manuscript and took full responsibility for the accuracy, originality, and integrity of the final published work.

Authorship Contribution Statement

Masluki conceived and designed the study, implemented the field experiment, curated the data, performed the formal analysis, prepared the visualizations, and wrote the original draft. Mutmainnah supervised the study and contributed to the methodology, validation, and review and editing of the manuscript. Erni Firdamayanti conducted the laboratory analyses and data collection, provided resources, and contributed to reviewing and editing. Sri Hastuty Saruman established the experimental setup, carried out field observations and data tabulation, and contributed to validation and to reviewing and editing. Ulfa Zakiyah Hamdani conducted the literature review, handled manuscript formatting and language editing, and contributed to proofreading and reviewing and editing. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests, personal relationships, institutional affiliations, or other conflicts of interest that could have appeared to influence the work reported in this manuscript.

Acknowledgements

The authors would like to express their gratitude to the Ministry of Higher Education, Science and Technology (KEMENDIKTISAINTEK) of the Republic of Indonesia for financial support provided through the 2025 Fundamental Research Scheme.

References

Abdel-Fattah, T. M., Mahmoud, M. E., Ahmed, S. B., Huff, M. D., Lee, J. W., & Kumar, S. (2015). Biochar from woody biomass for removing metal contaminants and carbon sequestration. *Journal of Industrial and Engineering Chemistry*, *22*, 103-109. https://doi.org/10.1016/j.jiec.2014.06.030

Abdul-Aziz, A. L., Haruna, A., & Baako, A. Y. (2026). Integrating biochar, compost, and chemical fertilizer improves maize yield and soil health in the Guinea savannah: Evidence from two cropping seasons in Northern Ghana. *Scientific Reports*, *16*, 2210. https://doi.org/10.1038/s41598-025-31886-2

Ahmed, S. F., Mehejabin, F., Chowdhury, A. A., Almomani, F., Khan, N. A., Badruddin, I. A., & Kamangar, S. (2024). Biochar

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

produced from waste-based feedstocks: Mechanisms, affecting factors, economy, utilization, challenges, and prospects. *GCB Bioenergy*, *16*(8), e13175. https://doi.org/10.1111/gcbb.13175

Alhaqi, R. A. H. (2024). Sago development strategy as a food security commodity in Indonesia. *Peatland Agriculture and Climate Change Journal*, *1*(2), 99-107. https://doi.org/10.61511/pacc.v1i2.2024.1902

Ali, A. M., & Bijay-Singh. (2025). Silicon: A crucial element for enhancing plant resilience in challenging environments. Journal of *Plant Nutrition*, *48*(3), 486–521. https://doi.org/10.1080/01904167.2024.2406479

Chaudhary, S., Bhatia, T., & Sindhu, S. S. (2024). Sustainable approach for management of organic waste agri-residues in soils for food production and pollution mitigation. In *Environmental nexus approach* (pp. 355-386). CRC Press. https://doi.org/10.1201/9781003408352

Edeh, I. G., & Mašek, O. (2022). The role of biochar particle size and hydrophobicity in improving soil hydraulic properties. *European Journal of Soil Science*, *73*(1), e13138. https://doi.org/10.1111/ejss.13138

Elkhlifi, Z., Iftikhar, J., Sarraf, M., Ali, B., Saleem, M. H., Ibranshahib, I., & Chen, Z. (2023). Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: A review. *Sustainability*, *15*(3), 2527. https://doi.org/10.3390/su15032527

Gontard, L. C., Batista, M., Salguero, J., & Calviño, J. J. (2018). Three-dimensional chemical mapping using non-destructive SEM and photogrammetry. *Scientific Reports*, *8*(1), 11000. https://doi.org/10.1038/s41598-018-29458-8

Hussan, M. U., Hussain, S., Hafeez, M. B., Ahmed, S., Hassan, M. U., Jabeen, S., & Wang, Q. (2024). Comparative role of calcium oxide nanoparticles and calcium bulk fertilizer to alleviate cadmium toxicity by modulating oxidative stress, photosynthetic performance and antioxidant-defense genes expression in alfalfa. *Plant Physiology and Biochemistry*, *215*, 109002. https://doi.org/10.1016/j.plaphy.2024.109002

Kaya, E., Siregar, A., Matulessy, D., Hasan, M., & Akollo, A. (2022). Soil chemistry character, the N, P, and K uptake, and the growth and yield of corn (*Zea mays* L.) due to the application of ela sago palm waste compost and liquid organic fertilizer in Ultisols. *Journal of Tropical Soils*, *27*(2), 49-58. https://doi.org/10.5400/jts.2022.v27i2.49-58

Li, Q., & Imran. (2025). Using biochar, compost, and dry-based organic amendments in combination with mycorrhizae for mitigating heavy metal contamination in soil. *International Journal of Phytoremediation*,*27*(10), 1502-1513. https://doi.org/10.1080/15226514.2025.2502458

Lima, J. R. D. S., Goes, M. D. C. C. D., Hammecker, C., Antonino, A. C. D., Medeiros, É. V. D., Sampaio, E. V. D. S. B., & Souza, R. (2021). Effects of poultry manure and biochar on Acrisol soil properties and yield of common bean: A short-term field experiment. *Agriculture*, *11*(4), 290. https://doi.org/10.3390/agriculture11040290

Lux, A., Lukačová, Z., Vaculík, M., Švubová, R., Kohanová, J., Soukup, M., & Bokor, B. (2020). Silicification of root tissues. *Plants*, *9*(1), 111. https://doi.org/10.3390/plants9010111

Mardiatmoko, G., Osok, R., Luhukay, M., & Hatulesila, J. W. (2025). Sago forests for food security and handling climate change in Indonesia. *Journal of Environmental & Earth Sciences*, *7*(1), 67-80. https://doi.org/10.30564/jees.v7i1.7190

Noor, R. S., Hussain, F., Abbas, I., Umair, M., & Sun, Y. (2023). Effect of compost and chemical fertilizer application on soil physical properties and productivity of sesame (*Sesamum indicum* L.). *Biomass Conversion and Biorefinery*, *13*(2), 905-915. https://doi.org/10.1007/s13399-020-01066-5

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2805

Omokaro, G. O., Kornev, K. P., Nafula, Z. S., Chikukula, A. A., Osayogie, O. G., & Efeni, O. S. (2025). Biochar for sustainable soil management: Enhancing soil fertility, plant growth and climate resilience. *Farming System*, 100167. https://doi.org/10.1016/j.farsys.2025.100167

Osaki, M., Tsuji, N., & Kato, T. (2024). Innovative eco-evaluation system for tropical peatlands. In *Tropical peatland eco-evaluation* (pp.3-67). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6790-2_1

Soplanit, A., Rumbarar, M. K., & Beding, P. (2021). Effect of sucker weight and seedling site on the growth of sago seedlings (*Metroxylon sago* Rottb.) in Papua. *IOP Conference Series: Earth and Environmental Science, 924*(1), 012085. https://doi.org/10.1088/1755-1315/924/1/012085

Trisia, M. A., Tachikawa, M., & Ehara, H. (2021). The role of the sago supply chain for rural development in Indonesia: A review and perspective. *Reviews in Agricultural Science*, *9*, 143–156. https://doi.org/10.7831/ras.9.0_143

Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *International Journal of Molecular Sciences*, *14*(4), 7370–7390. https://doi.org/10.3390/ijms14047370

Xu, S., Chen, J., Peng, H., Leng, S., Li, H., Qu, W., & Leng, L. (2021). Effect of biomass type and pyrolysis temperature on nitrogen in biochar, and the comparison with hydrochar. *Fuel*, *291*, 120128. https://doi.org/10.1016/j.fuel.2021.120128

Xu, L., Wu, K. C., Deng, Z. N., Huang, C. M., Verma, K. K., Pang, T., & Huang, H. R. (2024). Biochar and its impact on soil profile and plant development. *Journal of Plant Interactions*, *19*(1), 2401356. https://doi.org/10.1080/17429145.2024.2401356