



# Phosphorus Availability in Differently-Aged Growing Media within a Lebak Swamp Floating Agriculture System

Setya Hadi Purnama<sup>1</sup>, Akhmad Rizalli Saidy<sup>1,2\*</sup>, Abdul Haris<sup>1</sup>

(Received November 2025/Accepted May 2026)

## ABSTRACT

Floating agriculture, which utilizes local vegetation as a growing medium, is an adaptive innovation that enables year-round crop cultivation in the waterlogged conditions of lowland swamp ecosystems. However, the long-term capacity of these organic media to supply phosphorus (P), a critical nutrient, remains inadequately quantified. This study evaluated the phosphorus-supplying capacity of growing media of different ages (1 and 4 years) derived from identical vegetation sources. Media samples were collected from a 0–20 cm depth in two distinct cultivation systems: one year old media used for mustard greens (*Brassica juncea* L.) and four year old media used for eggplant (*Solanum melongena* L.). Analysis of chemical parameters (pH, available P, total P, and organic C) revealed that although the one year old media exhibited a higher pH (4.73–6.84) than the four year old media (4.34–6.05), available phosphorus showed no significant difference between them (1-year: 5.62–28.90 mg kg<sup>-1</sup>; 4-year: 6.00–24.46 mg kg<sup>-1</sup>). This indicates that the availability of phosphorus in these organic substrates is less strongly governed by pH than in mineral soils, which is in contrast to established mechanisms. Furthermore, the four year old media contained significantly higher levels of total P (158–1451 mg kg<sup>-1</sup>) and organic C (29.7–5.6 g kg<sup>-1</sup>) than the one year old media (total P: 137–703 mg kg<sup>-1</sup>; organic C: 4.7–29.7 g kg<sup>-1</sup>). These findings demonstrate that local vegetation-based growing media in floating agriculture systems possess a sustainable capacity for phosphorus supply, supporting the long-term viability of this cultivation approach in lowland swamp environments.

**Keywords:** floating farming system, lowland swamp, microbial decomposition, phosphatase, planting media age

## INTRODUCTION

Indonesia possesses significant agricultural potential in its swamplands, which cover approximately 9.5 million hectares, with approximately 4.5 million hectares suitable for development (Ministry of Agriculture Republic of Indonesia 2020). However, the utilization of this resource is severely constrained by extreme hydrological fluctuations, where water levels can rise by 1–3 m during the rainy season, thereby submerging conventional crops and disrupting soil nutrient cycles (Fahmid *et al.* 2022; Noor & Sosiawan 2019). These conditions necessitate innovative cultivation technologies that can circumvent waterlogging problems while harnessing the inherent fertility of the swamp ecosystem. By adopting such targeted technological approaches, these swamplands, once perceived as a major constraint,

can be transformed into a promising alternative food source, ultimately bolstering national food security.

The floating agriculture system represents a proven adaptive innovation designed to mitigate the challenges of high water levels in lowland swamp ecosystems. In Indonesian swamps, water depths often exceed 100 cm for up to six months per year, and various aquatic vegetation, such as water hyacinth (*Eichhornia crassipes*), mimosa (*Neptunia oleracea*), and water lettuce (*Salvinia molesta*), thrive unchecked, typically being regarded as invasive plants. The floating farming system, historically implemented in Bangladesh for over two centuries with documented sustainability and stable productivity, enables continuous crop cultivation throughout the year, unaffected by water-level fluctuations that can exceed 1–3 m during rainy seasons (Bala *et al.* 2020; Irfanullah *et al.* 2008). The use of floating rafts constructed from this aquatic vegetation offers a dual solution: overcoming the limitations of cultivation in permanently inundated swamps while simultaneously addressing the proliferation of invasive plants. The technology utilizes buoyant beds assembled from locally available organic materials, such as water hyacinth and other aquatic plants, which are then layered with organic growing media. Successfully adapted by Indonesian farmers for horticultural production in swamp

<sup>1</sup> Study Program of Soil Science, Faculty of Agriculture, Lambung Mangkurat University, South Kalimantan 70714, Indonesia

<sup>2</sup> Doctoral Program of Agricultural Science, Faculty of Agriculture, Lambung Mangkurat University, South Kalimantan 70714, Indonesia

\* Corresponding Author:  
E-mail: [asaidy@ulm.ac.id](mailto:asaidy@ulm.ac.id)

environments (Siaga *et al.* 2018; Wulandari *et al.* 2024), this approach provides significant advantages, including effective water stress management, efficient utilization of natural aquatic nutrients, and maintenance of the integrity of the swamp ecosystem. Consequently, floating agriculture serves not merely as a practical response to waterlogging constraints, but as a transformative, nature-based strategy that turns ecological nuisances into productive assets. By integrating indigenous knowledge with sustainable design, this system offers a replicable model for climate-resilient farming in other flood-prone regions, turning the challenge of persistent inundation into an opportunity for year-round food production.

The success of a floating raft farming system is determined by the ability of the plant medium to provide nitrogen, phosphorus, and potassium in readily available forms and quantities sufficient to support agriculture. Phosphorus (P) is a key component in energy transfer via adenosine triphosphate (ATP), driving root system development, and stimulating vital processes such as flowering, fruiting, and seed formation (Hawkesford *et al.* 2023). A deficiency in phosphorus manifests as clear physiological symptoms, including chlorosis evident in the yellowing of older leaves and significant retardation of overall plant growth (Reed 2019). Within the specific context of floating farming systems that rely on organic growing media, ensuring adequate phosphorus availability is particularly crucial because of the inherently low mineral phosphorus content in organic matter. Consequently, the selection and management of these organic substrates must prioritize a consistent and sustainable supply of phosphorus, facilitated by appropriate mineralization processes, to support crop productivity over multiple cultivation cycles.

In floating agriculture systems, plant nutrition fundamentally depends on the mineralization of organic growing media to release essential nutrients. This nutrient-release capacity is governed by the quality of the organic matter, which dictates the rate and efficiency of decomposition under stable environmental conditions (Marzi *et al.* 2020; Sarma *et al.* 2017). Amending soils with organic materials, such as crop residues and manure, enhances the quality of soil organic matter and subsequently increases P availability by releasing organic phosphate compounds during mineralization (Grzyb *et al.* 2020; Jindo *et al.* 2023). While the role of organic matter in supplying phosphorus has been well studied in conventional soils (Amadou *et al.* 2022; Rawal *et al.* 2022), the dynamics of available P in the floating media of different ages remain poorly understood. Understanding the ability of floating media of different ages to supply available phosphorus is essential for ensuring that floating farming systems serve as reliable long-term platforms for plant cultivation. Therefore, this study aimed to quantify the available phosphorus in organic growing media derived from similar vegetation but differing in

age (1 and 4 years). These findings are expected to offer critical insights into the long-term viability of organic substrates in floating systems, particularly regarding sustainable phosphorus supply for crop production in swamp environments.

## METHODS

### Study Site

This study was conducted in the lowland swamp ecosystem of Parigi Village, Daha Selatan District, Hulu Sungai Selatan Regency, South Kalimantan Province, Indonesia (2.638478° S, 115.080289° E). The site exhibits a distinct tropical wet climate, with annual rainfall (2020–2024) ranging from 1917 to 2754 mm distributed across 108–126 rainy days. A clear seasonal pattern characterizes the rainfall regime: the wettest period occurs from December to March, with monthly precipitation averaging 300–400 mm, whereas June to August represents a drier period with only 80–100 mm monthly. Temperature fluctuations are moderate, with daily averages ranging from 22°C to 34°C, peaking between September and October. The region maintains consistently high relative humidity (88–89%) throughout the year, contributing to perpetually saturated soil conditions. Notably, the swamp remains permanently inundated, with water levels fluctuating seasonally from 1–2 m during dry periods to 2–3 m in the rainy season, ensuring that the ecosystem never experiences complete desiccation.

This study was conducted using floating rafts of two different ages (one year and four years) to examine temporal variations in the system. The two floating media are situated close to each other, providing an identical hydrological background. The one year old floating media, made from fresh aquatic vegetation, represents a relatively young growing medium. In contrast, several studies have shown that organic matter eventually becomes exhausted and can no longer provide nutrients through microbial decomposition (Čapek *et al.* 2021; Hicks *et al.* 2021). Therefore, four-year old floating media, constructed from the same aquatic vegetation and layered structure as the one year media, were used as a comparison. Notably, these older rafts were replenished annually with the same type of organic matter used at the time of their manufacture. Both floating media systems receive neither inorganic fertilizer nor any nutrient replenishment beyond the annual addition of biomass. This annual replenishment allowed us to assess the ability of older floating media to continue supplying available phosphorus to support plant growth. Comparing rafts of different ages under identical replenishment regimes provides critical insight into the long-term nutrient dynamics of floating raft systems, thereby informing sustainable management practices for cultivation in swampland ecosystems.

Each raft was constructed using 15 bamboo poles measuring 13 m in length and 1.5 m in width, forming the fundamental floating structure and support base for the planting media. The bamboo poles were arranged in a crosswise pattern and securely fastened with nylon and rubber ropes to ensure the structural stability. A burlap sack was layered over the bamboo framework to create a contained planting bed foundation for the organic growing medium.

The one year and four years old floating rafts employed an identical layered structure for their growing media. The base layer, approximately 15 cm thick, consisted of fresh stems and roots of *Neptunia oleracea* placed directly atop the burlap sack. Subsequently, a second 15 cm layer composed exclusively of *Neptunia oleracea* roots was added. Finally, a third layer of similar thickness (15 cm) containing a mixture of *Eichhornia crassipes* and *Pistia stratiotes* completed the media structure. This assembled medium was then allowed to decompose in an open environment for three weeks, during which it settled to a total thickness of 20–25 cm. To maintain this optimal depth, annual replenishment with organic matter from *Eichhornia crassipes* and *Pistia stratiotes* is performed. In terms of cultivation, the one-year-old raft was utilized for mustard greens (*Brassica juncea* L.), while the four-year-old raft supported eggplant (*Solanum melongena* L.) production.

Both mustard greens and eggplants are horticultural crops with relatively short lifespans; mustard greens are harvested in 30–45 days, whereas eggplants require 45–75 days. Consequently, their overall nutrient requirements for growth are not significantly different from each other. Furthermore, the biomass (leaves and other plant tissues) of neither crop is returned to the growing medium; the medium receives additional organic matter only through annual replenishments. Therefore, any differences in phosphorus dynamics observed between the two growing media are more attributable to variations in organic matter content resulting from the age of the media than to differences in root system architecture.

### Sampling and Chemical Analysis of Growing Media

Planting media samples were collected from five floating rafts for each age category (one year and four year old) using a purposive random sampling approach. The criteria for selecting floating rafts are twofold: all rafts must be constructed from the same aquatic vegetation, and each raft must possess an identically structured layer. Three sampling points were randomly selected from each raft, resulting in 15 media samples per age group. Randomization was performed under the following conditions: sampling points located on the edge of the raft were excluded, and sampling was conducted at the midpoint between two plants exhibiting relatively similar growth patterns. The sampling procedure involved extracting approximately 300 g of planting media from each point using a soil

drill, reaching a depth of 0–20 cm from the media surface. Following collection, all samples were carefully processed to remove plant roots, sealed in plastic sample bags, and transported to the laboratory in cooling boxes to preserve their integrity for subsequent analyses.

In the laboratory, all planting media samples were consistently prepared and analyzed following established methodologies. The samples were air-dried and ground to achieve a uniform particle size of  $\leq 2.0$  mm. Soil pH was determined using the glass electrode method with a 1:5 soil-to-water ratio, followed by 30 min of shaking before measuring the suspension (McLean 1982). The organic carbon content was analyzed using the Walkley-Black method (Nelson & Sommers 1996). For phosphorus analysis, available phosphorus was extracted using Bray and Kurtz I solution and quantified spectrophotometrically (Jackson 1967), while total phosphorus was determined through digestion with 60%  $\text{HClO}_4$ , and the phosphorus content in the digest solution was measured spectrophotometrically at 660 nm (Olsen & Sommers 1982). These comprehensive analyses provided a complete characterization of the chemical properties of the planting medium samples.

### Statistical Analysis

To assess the effect of growing medium age on phosphorus dynamics, a comparative analysis of various phosphorus parameters was conducted between one year and four year old floating rafts. Statistical evaluation was performed using a parametric Independent Samples T-Test, which is specifically designed to detect significant differences between two independent groups. This methodological approach provides objective verification of whether an extended usage duration alters phosphorus availability and transformation in the growing media. All statistical analyses were performed using the Statistical Package for the Social Sciences (IBM SPSS) Version 31, ensuring rigorous and standardized data processing for reliable interpretation of the results.

## RESULTS AND DISCUSSION

### Chemical Characteristics of Organic Materials Used as Growing Media

The growing media used in this study were prepared from three aquatic plant species: *Pistia stratiotes*, *Eichhornia crassipes*, and *Neptunia oleracea*. These substrates exhibited a relatively uniform chemical composition, with organic-C, total-N, and total-P contents ranging from 301–368  $\text{g kg}^{-1}$ , 19–20  $\text{g kg}^{-1}$ , and 562–601  $\text{g kg}^{-1}$  (Table 1), respectively. Furthermore, the C/N ratios for all vegetation types fell within a narrow range of 15–18. This specific range is critical as it indicates that organic matter is prone to

rapid decomposition and net mineralization. This finding aligns with established principles, which posit that organic materials with a C/N ratio of  $\leq 18$  typically undergo mineralization, whereas those with a ratio of  $\geq 20$  tend to promote microbial immobilization of nutrients (Gale *et al.* 2006; Lazicki *et al.* 2020; Priatmadi *et al.* 2023).

The interactive effects of vegetational characteristics play a crucial role in determining the stability and functional performance of growing media. Notably, *Neptunia oleracea* contained the highest lignin concentration ( $382 \text{ g kg}^{-1}$ ), whereas *Eichhornia crassipes* possessed the highest levels of cellulose ( $346 \text{ g kg}^{-1}$ ) and hemicellulose ( $265 \text{ g kg}^{-1}$ ) (Table 1), respectively. This compositional profile is critical from a decomposition standpoint, as lignin, a complex phenylpropane polymer, forms protective bonds with structural carbohydrates, thereby significantly limiting the decay rate of organic matter (Hall *et al.* 2020; Xia *et al.* 2021). The high lignin content of *Neptunia oleracea* confirms its suitability as the primary layer in floating raft media; its inherent resistance to decomposition prolongs the functional lifespan of the media, directly supporting the long-term sustainability of the cultivation system. In contrast, the top layer, composed of *Pistia stratiotes* and *Eichhornia crassipes*, contains relatively high amounts of cellulose and hemicellulose, rendering it more susceptible to

rapid decomposition. Consequently, this stratified combination results in a growing medium where the bottom layer remains intact over time to serve as a stable physical support, while the top layer decomposes more readily to release essential nutrients for plant growth. This design not only optimizes the balance between medium longevity and nutrient availability, but also reduces the need for frequent replacement or external fertilization.

### Chemical Characteristics of Planting Media

The results revealed a significant difference in acidity levels between the two growing media at different ages. The one year old media exhibited a higher pH, with values ranging from 4.73 to 6.84 and an average of 6.16, classifying it as slightly acidic, according to the Soil Research Centre (1983). In contrast, the four year old media was more acidic, with a pH range of 4.34–6.05 and an average of 4.88 (Figure 1). This clear divergence demonstrates that the age of the organic growing media considerably influences its acidification over time.

The significant decrease in pH observed in the four year old growing media compared to the one year old media was primarily attributed to the dynamic biochemical and physicochemical processes associated with prolonged organic matter decomposition. As the media ages and the organic

Table 1 Characteristics of vegetation used as growing media in a floating agriculture system in tidal swamps

Characteristics of Growing Media	<i>Pistia stratiotes</i>	<i>Eichhornia crassipes</i>	<i>Neptunia oleracea</i>
Organic C ( $\text{g kg}^{-1}$ )	301.4	368.2	344.3
Total N ( $\text{g kg}^{-1}$ )	19.2	20.0	20.2
C/N ratio	15.7	18.4	17.0
Total P ( $\text{g kg}^{-1}$ )	60.1	56.2	59.1
Lignin ( $\text{g kg}^{-1}$ )	178.4	67.5	381.5
Selulosa ( $\text{g kg}^{-1}$ )	212.2	346.4	200.5
Hemiselulosa ( $\text{mg kg}^{-1}$ )	16.7	264.7	0.1

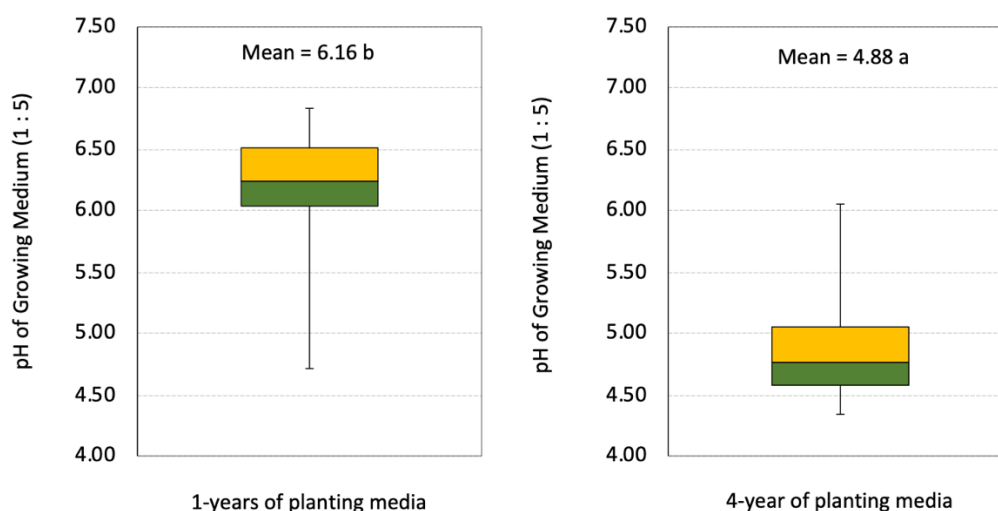


Figure 1 pH of planting media from floating farms in a lowland swamp, comparing 4-year-old and 1-year-old substrates. Mean pH values denoted by different letters differ significantly based on the t-test at  $p < 0.05$ .

matter reaches a more mature stage of decomposition, it generates various strong organic acids, including acetic, butyric, and fulvic acids, which subsequently dissociate and release  $H^+$  ions, thereby acidifying the medium (Bernard *et al.* 2022; Findlay 2021). This acidification phenomenon resulting from the breakdown of organic substrates is well documented in the literature, with similar pH declines reported in other studies on decomposing soil organic matter (Rukshana *et al.* 2011; Wang *et al.* 2013).

The nitrification process represents a key biochemical mechanism driving the acidification of the growing medium over four years. This phenomenon is initiated when organic nitrogen is mineralized into ammonium ( $NH_4^+$ ), which is subsequently oxidized by microbes to nitrate ( $NO_3^-$ ) in a reaction that liberates protons ( $H^+$ ), thereby directly elevating acidity (Wang *et al.* 2020; Zhang *et al.* 2020). As long as a sufficient supply of readily decomposable nitrogen substrates is maintained by the addition of organic matter, this acid-producing cycle continues unabated. The resultant sustained release of  $H^+$  ions provides a fundamental explanation for the characteristically lower pH measured in the four year old growing medium.

Analysis of the growing media revealed no significant difference in the available phosphorus content between the one year old and four year old media, as illustrated in Figure 2. The available phosphorus in the one year old media ranged from 5.62 to 28.90  $mg\ kg^{-1}$  (average: 15.01  $mg\ kg^{-1}$ ), whereas the four year old media ranged from 6.00 to 24.46  $mg\ kg^{-1}$  (average: 15.42  $mg\ kg^{-1}$ ) (Figure 2). Notably, the mean available phosphorus content for both media ages fell within a classification considered very high (Soil Research Center 1983), indicating that the age of the media, up to four years, did not negatively impact

the immediate bioavailability of phosphorus for plant uptake.

The consistent availability of phosphorus in both the one year and four year old growing media is a direct consequence of their shared origin as pure organic matter devoid of mineral soil components. Since both media were derived from aquatic vegetation of identical composition, they possessed a similar C/P ratio below 200, a critical threshold that favors net mineralization of phosphorus over immobilization. Organic matter with a C/P ratio  $<200$  facilitates the release of plant-available phosphorus, whereas a ratio  $>300$  typically leads to microbial immobilization, locking up the nutrients (Chen *et al.* 2022; Khan *et al.* 2025; Stevenson & Cole 1999). While the decomposition dynamics differ between media ages and with rapid mineralization and concurrent microbial immobilization in the fresh one year old media versus a slower, sustained release from accumulated humus in the four year old media—these processes establish a dynamic equilibrium. This biological balance between mineralization and immobilization ultimately results in statistically similar levels of available phosphorus, underscoring that its availability in these organic systems is predominantly governed by microbial activity rather than chemical fixation (Achat *et al.* 2016).

The exclusive organic composition of both growing media, devoid of soil mineral components, precluded the primary mechanism of phosphorus (P) fixation typically mediated by aluminium (Al), iron (Fe), or calcium (Ca) ions in mineral soils. The results demonstrated that, although a significant pH difference existed between the two media (Figure 1), their available phosphorus content did not differ significantly (Figure 2). This finding suggests that phosphorus availability in these organic substrates is less strongly controlled by pH than in mineral soils, where pH is the

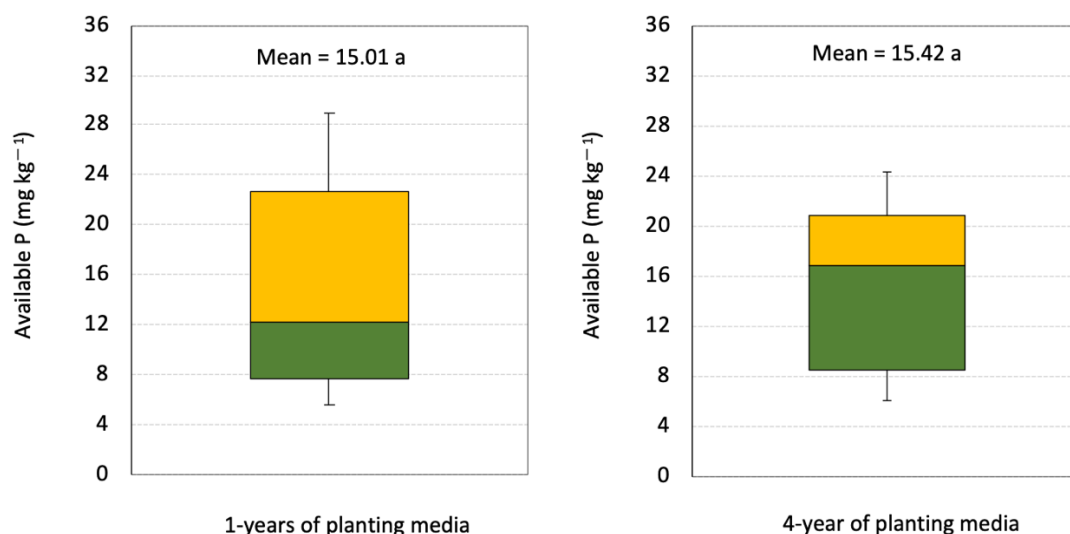


Figure 2 Available phosphorous of planting media from floating farms in a lowland swamp, comparing 4-year-old and 1-year-old substrates. Mean available phosphorous values denoted by different letters differ significantly based on the t-test at  $p < 0.05$ .

primary determinant of P solubility (Barrow *et al.* 2020; Ding *et al.* 2020). The absence of mineral fixation mechanisms decouples P availability from acidity in this system. This characteristic is highly advantageous for long-term cultivation, as the availability of phosphorus remains stable and does not decline with the age of the medium, thereby supporting the sustainable use of these organic substrates for extended plant production cycles.

The analysis of total phosphorus revealed a distinct accumulation in the older growing medium, with the four year old medium containing a higher average total phosphorus content (581 mg kg<sup>-1</sup>) than the one year old medium (496 mg kg<sup>-1</sup>) (Figure 3). The measured ranges were 158–1451 mg kg<sup>-1</sup> for the four year old media and 137–1703 mg kg<sup>-1</sup> for the one year old media (Figure 3). Notably, despite this difference in concentration, the total phosphorus content in both media was classified as high according to the soil property assessment criteria of the Soil Research Centre (1983). This indicates that both substrates possess a substantial reservoir of phosphorus, with older media showing greater accumulation over time.

The lower total phosphorus content observed in the one-year-old growing media was directly linked to the cumulative export of phosphorus through repeated harvests of the pak choy crop. Pak choy, an annual vegetable with a short life cycle (30–45 days), shallow root system, and limited biomass return, constitutes an extractive system that removes phosphorus without sufficient compensatory input. Without adequate fertilization to replenish this loss, the total phosphorus pool in the medium inevitably declines over time. This phenomenon is well established in agricultural science; the removal of plant biomass is a primary pathway for phosphorus export from a cultivation system, leading to a negative phosphorus balance when outputs exceed inputs. This results in a significant drawdown of soil phosphorus reserves over time, as demonstrated by

long-term studies (Blake *et al.* 2000; Rowe *et al.* 2016). Consequently, in any cropping system where phosphorus off-take consistently surpasses its replenishment, a negative nutrient balance accrues, ultimately depleting the total phosphorus content, a principle further supported by recent research (Magaya *et al.* 2025; Margenot *et al.* 2024).

The analysis revealed a clear accumulation of organic carbon over time, with the four year old planting media exhibiting a significantly higher organic carbon content than the one year old media. Quantitatively, the one year old media had an organic C content ranging from 4.7 to 29.7 g kg<sup>-1</sup> (average: 19.5 g kg<sup>-1</sup>), whereas the four year old media showed a substantially greater range of 5.4–65.6 g kg<sup>-1</sup> with an average of 36.8 g kg<sup>-1</sup> (Figure 4). Notably, according to the soil chemical characteristic assessment criteria from the Soil Research Centre (1983), the organic C content in both media ages is classified as "very high." This indicates that while the four year old media underwent significant carbon accumulation, even the younger media maintained an excellent level of soil organic matter.

The significantly higher organic carbon content observed in the four year old growing media compared to the one year old media is a direct result of the suppressed decomposition rate under the persistently anaerobic conditions of the swamp environment. Older media undergo a longer but incomplete decomposition cycle, as the oxygen-deficient environment significantly inhibits the activity of decomposer microorganisms. This phenomenon is primarily driven by anaerobiosis, which drastically slows organic matter mineralization. In wetland ecosystems, decomposition rates under anaerobic conditions are typically only 10-50% of those observed in aerobic environments (Mitsch & Gosselink 2015). Consequently, organic matter accumulated over the four-year period does not fully decompose, leading to net accumulation of organic carbon. This suggests that the rate of organic matter breakdown was lower

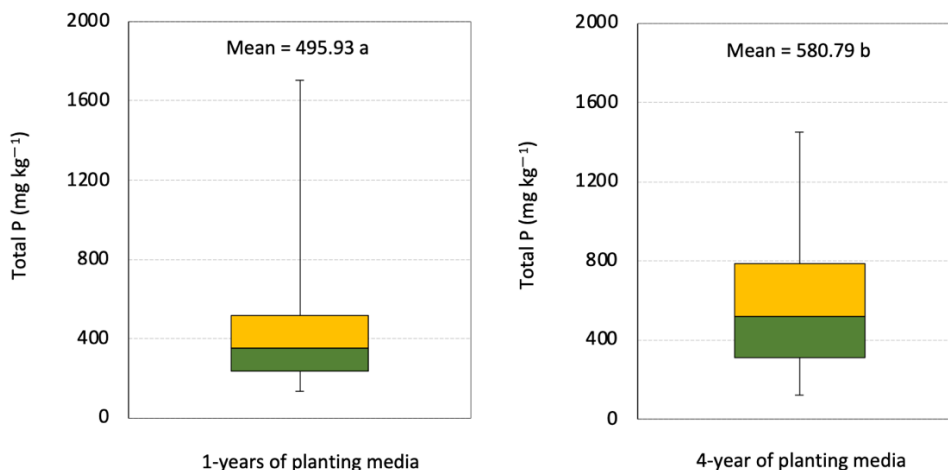


Figure 3 Total phosphorous of planting media from floating farms in a lowland swamp, comparing 4-year-old and 1-year-old substrates. Mean total phosphorous values denoted by different letters differ significantly based on the t-test at  $p < 0.05$ .

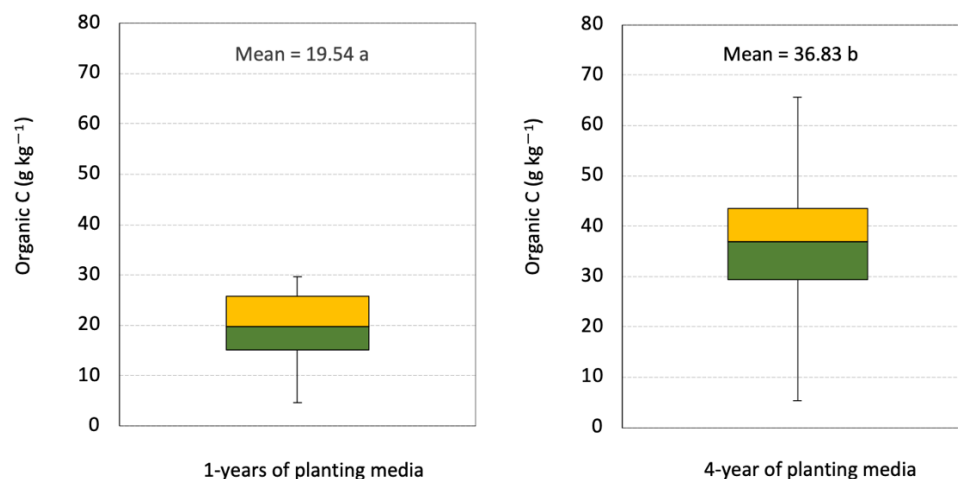


Figure 4 Organic carbon of planting media from floating farms in a lowland swamp, comparing 4-year-old and 1-year-old substrates. Mean organic carbon values denoted by different letters differ significantly based on the t-test at  $p < 0.05$ .

than the rate of organic matter addition. Consequently, as long as the existing environmental conditions are maintained, long-term stabilization of organic carbon will occur. This finding supports the sustainability of floating raft systems with regular organic matter replenishment. This mechanism aligns with the established principle that organic matter buildup in wetlands is a function of an imbalance between input from primary productivity and output through decomposition, with oxygen limitation being the key factor that retards the latter process (Reddy *et al.* 2022). Therefore, the extended duration of media in this anaerobic system directly facilitates greater sequestration of organic carbon.

This unique anaerobic system cannot be replicated under different environmental conditions without adjustments. If this floating raft is implemented under conditions that are too dry, the growing medium will decompose further, potentially reducing its structural stability (Plaza-Bonilla *et al.* 2022). Conversely, if the system becomes overly anaerobic, organic matter mineralization proceeds very slowly, resulting in low nutrient availability for plant growth (Lin *et al.* 2021). Therefore, maintaining an optimal balance between aerobic and anaerobic conditions within the floating raft is essential to simultaneously preserve medium longevity and ensure an adequate nutrient supply for sustainable crop cultivation. In practice, site-specific water management is required to preserve the unique functionality of this system. The results of this study indicate that a growing medium used for more than four years can still function optimally to support plant growth. This sustained ability is attributable to the annual organic matter replenishment. Thus, regular organic matter addition can effectively extend the functional lifespan of floating raft media, ensuring long-term productivity in swamp cultivation systems without complete replacement.

Although one-year-old and four-year-old floating media were used to cultivate different crops—mustard

greens on the one-year media and eggplants on the four-year media—the effect of crop type on organic carbon content in the floating media was negligible. Both plants have nearly the same ability to contribute to biomass as a carbon source, and their respective contributions are relatively similar, each providing very little biomass. Consequently, the primary source of organic matter in both floating media does not come from the crops themselves but from the annual external addition of organic matter to the growing medium. Therefore, differences in organic carbon content between media were more strongly influenced by media age than by crop type.

## CONCLUSION

The pH of the one year old growing medium was higher than that of the four year old medium, attributable to biochemical and physicochemical processes that accumulate  $H^+$  ions in the older medium through prolonged organic matter decomposition and acid production. Despite this significant pH difference, the availability of phosphorus was similar in the two media. This indicates that in these organic substrates, phosphorus availability is not primarily governed by pH, in contrast to the established paradigm in mineral soil systems, where pH critically controls phosphorus solubility. Instead, phosphorus dynamics in both media are predominantly regulated by biological processes, specifically through the dynamic equilibrium between microbial mineralization and immobilization. Furthermore, the study revealed that the four year old medium contained higher total phosphorus and organic carbon content, where the slow decomposition rate under anaerobic conditions combined with continuous biomass input from long-cycle crops facilitated the accumulation of these elements. Collectively, these results demonstrate that swamp vegetation-based

planting media can establish self-sustaining phosphorus dynamics that support plant growth, highlighting their potential for developing sustainable agricultural systems using floating raft technology in swamp ecosystems.

## ACKNOWLEDGEMENT

The authors express their sincere gratitude to Lambung Mangkurat University for the financial support provided through the Competency-Based Research Scheme (Contract No. 1331/UN8/PG/2024).

## REFERENCES

- Achat DL, Pousse N, Nicolas M, Brédoire F, Augusto L. 2016. Soil properties controlling inorganic phosphorus availability: general results from a national forest network and a global compilation of the literature. *Biogeochemistry*. 127 (2): 255–272. <https://doi.org/10.1007/s10533-015-0178-0>
- Amadou I, Faucon M-P, Houben D. 2022. Role of soil minerals on organic phosphorus availability and phosphorus uptake by plants. *Geoderma*. 428. 116125. <https://doi.org/10.1016/j.geoderma.2022.116125>
- Bala H, Ghosh A, Kazal MMH, Rahman M, Sultana M, Sujana M. 2020. Floating gardening in Bangladesh: a sustainable income generating activity in wetland areas. *International Journal of Agricultural Research, Innovation and Technology*. 10(1): 87–93. <https://doi.org/10.3329/ijarit.v10i1.48098>
- Barrow NJ, Debnath A, Sen A. 2020. Measurement of the effects of pH on phosphate availability. *Plant and Soil*. 454(1): 217–224. <https://doi.org/10.1007/s11104-020-04647-5>
- Bernard L, Basile-Doelsch I, Derrien D, Fanin N, Fontaine S, Guenet B, Karimi B, Marsden C, Maron P-A. 2022. Advancing the mechanistic understanding of the priming effect on soil organic matter mineralisation. *Functional Ecology*. 36(6): 1355–1377. <https://doi.org/10.1111/1365-2435.14038>
- Blake L, Mercik S, Koerschens M, Moskal S, Poulton PR, Goulding KWT, Weigel A, Powlson DS. 2000. Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. *Nutrient Cycling in Agroecosystems*. 56(3): 263–275. <https://doi.org/10.1023/A:1009841603931>
- Čapek P, Choma M, Tahovská K, Kaňa J, Kopáček J, Šantrůčková H. 2021. Coupling the resource stoichiometry and microbial biomass turnover to predict nutrient mineralization and immobilization in soil. *Geoderma*. 385, 114884. <https://doi.org/10.1016/j.geoderma.2020.114884>
- Chen J, Jia B, Gang S, Li Y, Li F-C, Mou XM, Kuzyakov Y, Li XG. 2022. Decoupling of soil organic carbon and nutrient mineralization across plant communities as affected by microbial stoichiometry. *Biology and Fertility of Soils*. 58(6): 693–706. <https://doi.org/10.1007/s00374-022-01655-8>
- Ding W, Clode PL, Lambers H. 2020. Effects of pH and bicarbonate on the nutrient status and growth of three *Lupinus* species. *Plant and Soil*. 447(1): 9–28. <https://doi.org/10.1007/s11104-019-03980-8>
- Fahmid IM, Wahyudi, Agustian A, Aldillah R, Gunawan E. 2022. The potential swamp land development to support food estates programmes in Central Kalimantan, Indonesia. *Environment and Urbanization ASIA*. 13 (1): 44–55. <https://doi.org/10.1177/09754253221078178>
- Findlay SEG. (2021). Chapter 4 - Organic Matter Decomposition. In KC Weathers, DL Strayer, GE Likens (Eds.), *Fundamentals of Ecosystem Science (Second Edition)* (pp. 81–102). Academic Press. <https://doi.org/10.1016/B978-0-12-812762-9.00004-6>
- Gale ES, Sullivan DM, Cogger CG, Bary AI, Hemphill DD, Myhre EA. 2006. Estimating plant-available nitrogen release from manures, composts, and specialty products *Journal of Environmental Quality*. 35(6): 2321–2332. <https://doi.org/10.2134/jeq2006.0062>
- Grzyb A, Wolna-Maruwka A, Niewiadomska A. (2020). Environmental factors affecting the mineralization of crop residues. *Agronomy*, 10(12).
- Hall SJ, Huang W, Timokhin VI, Hammel KE. 2020. Lignin lags, leads, or limits the decomposition of litter and soil organic carbon. *Ecology*. 101(9): e03113. <https://doi.org/10.1002/ecs.3113>
- Hawkesford MJ, Cakmak I, Coskun D, De Kok LJ, Lambers H, Schjoerring JK, White PJ. (2023). Functions of macronutrients. In Z Rengel, I Cakmak, PJ White (Eds.), *Marschner's Mineral Nutrition of Plants (Fourth Edition)* (pp. 201–281). Academic Press. <https://doi.org/10.1016/B978-0-12-819773-8.00019-8>
- Hicks LC, Lajtha K, Rousk J. 2021. Nutrient limitation may induce microbial mining for resources from persistent soil organic matter. *Ecology*. 102(6): e03328. <https://doi.org/10.1002/ecs.3328>
- Irfanullah HM, Adrika A, Ghani A, Khan ZA, Rashid MA. 2008. Introduction of floating gardening in the north-eastern wetlands of Bangladesh for nutritional security and sustainable livelihood. *Renewable*

- Agriculture and Food Systems*. 23(2): 89–96. <https://doi.org/10.1017/S1742170507002074>
- Jackson ML. (1967). Phosphorous determination for soils. In ML Jackson (Ed.), *Soil Chemical Analysis* (pp. 134–182). Constables.
- Jindo K, Audette Y, Olivares FL, Canellas LP, Smith DS, Paul Voroney R. 2023. Biotic and abiotic effects of soil organic matter on the phytoavailable phosphorus in soils: a review. *Chemical and Biological Technologies in Agriculture*. 10(1): 29. <https://doi.org/10.1186/s40538-023-00401-y>
- Khan KS, Naveed M, Ditta A, Alam T, Mumtaz MZ, Abbas A, Manzoni S, Li L. 2025. Soil C/P Stoichiometry Mediated Microbially Driven Phosphorus Mobilization: New Insight in Soil P Management. *Journal of soil science and plant nutrition*. 25(3): 7691–7709. <https://doi.org/10.1007/s42729-025-02624-4>
- Lazicki P, Geisseler D, Lloyd M. 2020. Nitrogen mineralization from organic amendments is variable but predictable. *Journal of Environmental Quality*. 49(2), 483-495. <https://doi.org/10.1002/jeq2.20030>
- Lin Y, Campbell AN, Bhattacharyya A, DiDonato N, Thompson AM, Tfaily MM, Nico PS, Silver WL, Pett-Ridge J. 2021. Differential effects of redox conditions on the decomposition of litter and soil organic matter. *Biogeochemistry*. 154(1), 1-15. <https://doi.org/10.1007/s10533-021-00790-y>
- Magaya S, Magid J, Hermann L, Schulp CJE. 2025. Phosphorus removal and use in organic crop farming in the EU. *Nutrient Cycling in Agroecosystems*. 130(1), 91-110. <https://doi.org/10.1007/s10705-024-10379-0>
- Margenot AJ, Zhou S, Xu S, Condrón LM, Metson GS, Haygarth PM, Wade J, Agyeman PC. 2024. Missing phosphorus legacy of the Anthropocene: Quantifying residual phosphorus in the biosphere. *Global Change Biology*. 30(6), e17376. <https://doi.org/10.1111/gcb.17376>
- Marzi M, Shahbazi K, Kharazi N, Rezaei M. 2020. The Influence of Organic Amendment Source on Carbon and Nitrogen Mineralization in Different Soils. *Journal of soil science and plant nutrition*. 20(1): 177–191. <https://doi.org/10.1007/s42729-019-00116-w>
- McLean EO. (1982). Soil pH and lime requirement. In AL Page DR Keeney (Eds.), *Methods of Soil Analysis Part 2: Chemical and Biological Properties* (pp. 199–224). Soil Science Society of America. <https://doi.org/10.2134/agronmonogr9.2.2ed.c12>
- Ministry of Agriculture Republic of Indonesia. (2020). *Agricultural Statistics 2020*. Center for Agricultural Data and Information System, Ministry of Agriculture Republic of Indonesia.
- Mitsch WJ, Gosselink JG. (2015). *Wetlands*. John Wiley & Sons, Inc., Hoboken, New Jersey.
- Nelson DW, Sommers LE. (1996). Total carbon, organic carbon and organic matter. In DL Sparks (Ed.), *Methods of Soil Analysis Part 3: Chemical Methods*. (pp. 961-1011). Soil Science Society of America-American Society of Agronomy Inc. <https://doi.org/10.2136/sssabookser5.3.c34>
- Noor M, Sosiawan H. (2019). Water management in tidal swamps farming: From indigenous knowledge to improved technology. In Y Sulaeman, L Poogio, B Minasny, D Nursyamsi (Eds.), *Tropical Wetlands - Innovation in Mapping and Management*. CRC Press. <https://doi.org/10.1201/9780429264467>
- Olsen SR, Sommers LE. (1982). Phosphorus. In AL Page, RH Miller, DR Keeney (Eds.), *Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties* (Second Edition ed., pp. 403-430). American Society of Agronomy, Inc., and Soil Science Society of America, Inc. <https://doi.org/10.2134/agronmonogr9.2.2ed.c24>
- Plaza-Bonilla D, Mary B, Valé M, Justes E. 2022. The sensitivity of C and N mineralization to soil water potential varies with soil characteristics: Experimental evidences to fine-tune models. *Geoderma*. 409, 115644. <https://doi.org/10.1016/j.geoderma.2021.115644>
- Priatmadi BJ, Septiana M, Mulyawan R, Saidy AR. (2023). Nitrogen mineralization of two different reclaimed-mining soils treated with organic matter and coal-fly ash. Conference Proceeding: The 9th Annual International Seminar on Trends in Science and Science Education (AISTSSE) 2022, <https://doi.org/10.2478/9788367405195-034>
- Rawal N, Pande KR, Shrestha R, Vista SP. 2022. Phosphorus and potassium mineralization as affected by phosphorus levels and soil types under laboratory condition. *Agrosystems, Geosciences & Environment*. 5 (1): e20229. <https://doi.org/10.1002/agg2.20229>
- Reddy KR, DeLaune RD, Inglett PW. (2022). *Biogeochemistry of Wetlands: Science and Applications* (2nd Edition ed.). CRC Press. <https://doi.org/10.1201/9780429155833>
- Reed JF. (2019). Visual plant symptoms as indicators of mineral nutrient deficiencies. In DP Plucknett (Ed.), *Detecting Mineral Nutrient Deficiencies in Tropical and Temperate Crops* (pp. 1–12). CRC Press. <https://doi.org/10.1201/9780429035258>
- Rowe H, Withers PJA, Baas P, Chan NI, Doody D, Holiman J, Jacobs B, Li H, MacDonald GK,

- McDowell R, Sharpley AN, Shen J, Taheri W, Wallenstein M, Weintraub MN. 2016. Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security. *Nutrient Cycling in Agroecosystems*. 104(3): 393–412. <https://doi.org/10.1007/s10705-015-9726-1>
- Rukshana F, Butterly CR, Baldock JA, Tang C. 2011. Model organic compounds differ in their effects on pH changes of two soils differing in initial pH. *Biology and Fertility of Soils*. 47(1): 51–62. <https://doi.org/10.1007/s00374-010-0498-0>
- Sarma B, Borkotoki B, Narzari R, Katak R, Gogoi N. 2017. Organic amendments: Effect on carbon mineralization and crop productivity in acidic soil. *Journal of Cleaner Production*. 152: 157–166. <https://doi.org/10.1016/j.jclepro.2017.03.124>
- Siaga E, Lakitan B, Bernas SM, Wijaya A, Lisda R, Ramadhani F, Widuri LI, Kartika K, Meihana M. 2018. Application of floating culture system in chili pepper (*Capsicum annum* L.) during prolonged flooding period at riparian wetland in Indonesia. *Australian Journal of Crop Science*. 12(5): 808–816. <https://doi.org/10.21475/ajcs.18.12.05.PNE1007>
- Soil Research Centre. (1983). *Guide for Soil Physics and Chemistry Analyses*. Soil Research Institute, Indonesian Agency for Agricultural Research and Development.
- Stevenson FJ, Cole MA. (1999). *Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients*. (2nd ed.). John Wiley & Sons.
- Wang J, Tu X, Zhang H, Cui J, Ni K, Chen J, Cheng Y, Zhang J, Chang SX. 2020. Effects of ammonium-based nitrogen addition on soil nitrification and nitrogen gas emissions depend on fertilizer-induced changes in pH in a tea plantation soil. *Science of the Total Environment*. 747, 141340. <https://doi.org/10.1016/j.scitotenv.2020.141340>
- Wang Y, Tang C, Wu J, Liu X, Xu J. 2013. Impact of organic matter addition on pH change of paddy soils. *Journal of Soils and Sediments*. 13(1): 12–23. <https://doi.org/10.1007/s11368-012-0578-x>
- Wulandari NB, Nugroho A, Saidy AR, Priatmadi BJ. 2024. Amelioration of planting media in chili cultivation with floating system in lebak swamp. *International Journal of Biosciences*. 24(3): 30–41. <https://doi.org/http://dx.doi.org/10.12692/ijb/24.3.30-41>
- Xia S, Song Z, Li Q, Guo L, Yu C, Singh BP, Fu X, Chen C, Wang Y, Wang H. 2021. Distribution, sources, and decomposition of soil organic matter along a salinity gradient in estuarine wetlands characterized by C:N ratio,  $\delta^{13}\text{C}$ - $\delta^{15}\text{N}$ , and lignin biomarker. *Global Change Biology*. 27(2): 417–434. <https://doi.org/10.1111/gcb.15403>
- Zhang Y, Dai S, Huang X, Zhao Y, Zhao J, Cheng Y, Cai Z, Zhang J. 2020. pH-induced changes in fungal abundance and composition affects soil heterotrophic nitrification after 30 days of artificial pH manipulation. *Geoderma*. 366, 114255. <https://doi.org/10.1016/j.geoderma.2020.114255>