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Enhancing shallot growth and yield performance through peat-derived humic acid amelioration in tidal swampland: A sustainable approach to marginal land utilization

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Abstract: Tidal swamplands represent one of Indonesia's most extensive yet underutilized agricultural resources, covering approximately 20.1 million hectares. These marginal lands possess significant potential for horticultural crop production, particularly for high-value crops such as shallots (*Allium cepa* L. *Aggregatum*). However, inherent challenges including soil acidity, aluminum toxicity, nutrient deficiency, and periodic waterlogging severely limit crop productivity. This study investigated the effectiveness of peat-derived humic acid amelioration on shallot cultivation in tidal swampland conditions of Riau Province, Indonesia. A split-plot field experiment evaluated three high-yielding varieties (Tajuk, Bima, and Manjung) and five humic acid application rates (0, 0.08, 0.16, 0.24, and 0.32 g plant^{-1}) in a randomized complete block design with three replications. Initial soil analysis revealed highly acidic conditions with pH 4.20 and elevated aluminum concentration of 5.36 cmol(+) kg^{-1}. Results demonstrated that the Bima variety consistently outperformed other varieties, achieving maximum plant height of 36.42 cm and total plant weight of 4.57 g. Humic acid application at 0.32 g plant^{-1} produced optimal results, generating maximum fresh weight productivity of 10.5 tons hectare^{-1}, representing a 275% increase over control treatments (2.8 tons hectare^{-1}). Significant interactions between varietal selection and humic acid application demonstrated synergistic effects in overcoming soil constraints, indicating that integrated management strategies combining appropriate varietal selection with targeted soil amelioration offer a viable sustainable approach for improving shallot cultivation in marginal tidal swampland environments.

Keywords: tidal swampland, humic acid, shallot cultivation, marginal land agriculture, sustainable soil management, organic ameliorant.

Introduction

Tidal swamplands represent one of Indonesia's most extensive yet underutilized agricultural resources, covering approximately 20.1 million hectares across the archipelago (Sulaiman et al., 2019). These marginal lands possess significant potential for horticultural crop production, particularly for high-value crops such as shallots *(Allium cepa L. Aggregatum),* which constitute a critical component of Indonesia's agricultural economy and food security (Haitami et al., 2024). However, the inherent challenges of tidal swampland cultivation, including soil acidity, aluminum toxicity, nutrient deficiency, and periodic waterlogging, severely limit crop productivity and agricultural sustainability in these ecosystems (Alwi et al., 2021).

Current agricultural practices in tidal swamplands predominantly rely on synthetic fertilizers and conventional soil amendments to address these constraints. However, these approaches often prove economically unfeasible for smallholder farmers and environmentally unsustainable due to their contribution to greenhouse gas emissions and soil degradation (Chen et al., 2022). Recent advances in soil science have highlighted the potential of organic ameliorants, particularly humic substances derived from peat materials, as effective solutions for improving soil quality and crop performance in acidic, marginal soils (Ampong et al., 2022). Humic acids, as complex organic polymers, possess unique properties including high cation exchange capacity, pH buffering ability, and metal chelation capabilities (Boguta et al., 2019), making them particularly suitable for addressing the multiple soil constraints prevalent in tidal swampland agriculture.

The application of humic acid ameliorants has demonstrated promising results in various agricultural systems, with documented improvements in soil structure, nutrient availability, and plant stress tolerance. A comprehensive meta-analysis by Ma et al. (2022) revealed that humic acid amendment significantly increased crop yield by 12%, nitrogen use efficiency by 27%, and nitrogen uptake by 17%, on average. Li et al. (2021) demonstrated through a three-year field experiment that humic acid treatment increased the yield and quality of continuous cropping peanuts compared with control experiments, attributed to improved soil physicochemical properties and enhanced microbial diversity. Similarly, recent studies by Maji et al. (2017) confirmed that plants are more stress-tolerant, productive, healthier, and yield better quality in soil with high humic acid content. However, the majority of existing research has focused on upland crops and conventional agricultural systems, with limited investigation into the specific responses of horticultural crops to humic acid applications in tidal swampland conditions.

Despite the growing body of literature on humic acid applications in agriculture, significant knowledge gaps remain regarding the optimization of peat-derived humic acid ameliorants for shallot cultivation in tidal swamplands. Agricultural development in tidal swampland faces various challenges such as exposure to pyrite layer and generally shallow bottom of less than 50 cm, thick, raw, hydrophobic peat, water stress and seawater intrusion, and attack of plant pests and diseases (Turhadi et al., 2019). The complex interactions between humic acid properties, soil chemistry, and plant physiology under fluctuating water table conditions characteristic of tidal ecosystems require targeted research to develop effective application strategies (Olk et al., 2018). Furthermore, the variability in peat humic acid composition and its impact on ameliorant effectiveness across different tidal swampland soil types remains poorly understood, particularly considering the specific requirements for land selection in these environments where pyrite depth >100 cm, peat thickness >3 m with sapric maturity level, and soil pH ranging from 5.0 to 6.0 are critical factors (Fernández-Caliani et al. 2021).

The novelty of this research lies in its comprehensive investigation of peat-derived humic acid ameliorants specifically formulated for tidal swampland conditions and their application to shallot cultivation. This study introduces an innovative approach to sustainable marginal land utilization by combining indigenous organic resources (peat humic acids) with precision agriculture techniques tailored to the unique characteristics of tidal ecosystems. The research addresses the critical need for environmentally sustainable and economically viable soil improvement strategies that can enhance agricultural productivity while maintaining ecosystem integrity in these sensitive environments. Furthermore, this study contributes to the understanding of how organic amendments can improve soil properties while potentially reducing carbon dioxide emissions and peat hydrophobicity issues commonly associated with tidal peatlands.

The primary objective of this research is to evaluate the effectiveness of peat-derived humic acid ameliorants in enhancing shallot growth performance, yield quality, and nutrient use efficiency under tidal swampland conditions. Specific objectives include: (1) characterizing the physico-chemical properties of peat humic acid ameliorants and their interaction with tidal swampland soils; (2) determining optimal application rates and timing for humic acid ameliorants in shallot cultivation; (3) assessing the impact of humic acid applications on soil quality parameters, plant physiological responses, and crop productivity; and (4) developing sustainable soil management recommendations for shallot cultivation in tidal swampland agriculture.

Result and Discussion

Soil chemical properties analysis

Based on the initial soil chemical and physical properties presented, soil conditions indicate several critical limitations for agricultural production. Soil acidity appears severely constrained, with pH H_2O of 4.26 and pH KCl of 4.20, both classified as very acidic (Table 1). Such low pH values typically restrict nutrient availability and increase aluminum toxicity, which can severely impair root development and overall plant growth (Sharma et al., 2025).

Organic matter content at 3.67% falls within the moderate range, suggesting reasonable biological activity and nutrient retention capacity. However, total nitrogen content of 0.24% is relatively low, potentially limiting crop productivity without supplemental nitrogen fertilization (Pandit et al., 2025). Phosphorus availability presents a critical concern, with P_2O_5-Bray I measuring only 4.12 ppm, classified as very low. This deficiency is particularly problematic in acidic soils where phosphorus fixation by aluminum and iron compounds severely restricts plant uptake (Johan et al., 2021). Potassium content at 0.35 cmol(+) kg^{-1} is categorized as low, while calcium and magnesium levels of 5.32 and 1.78 cmol(+) kg^{-1}, respectively, are also insufficient for optimal plant nutrition.

Cation exchange capacity (CEC) of 29.54 cmol(+) kg^{-1} is classified as high, indicating good nutrient retention potential, though base saturation at only 14.72% is extremely low, suggesting that exchange sites are predominantly occupied by acidic cations rather than essential nutrients (Tao, 2019). Iron content appears excessive at 473 ppm, which combined with low pH may contribute to nutrient imbalances and potential toxicity issues. Soil texture analysis reveals a silty loam composition (27.71% sand, 43.15% silt, 18.57% clay), providing adequate drainage while maintaining reasonable water and nutrient holding capacity. Comprehensive soil amelioration strategies including liming to raise pH, organic matter incorporation, and balanced fertilization are essential to overcome these limitations and establish productive agricultural systems.

Table 1. Initial soil chemical and physical properties.

Parameter		Result	Criteria
pH H_2O		4.26	Very Acid
pH KCl		4.19	Very Acid
Water Content (%)		3.67	
C-Organic (%)		2.30	Very High
N-Total(%)		0.24	Moderate
P_2O_5 Bray I (ppm)		41.2	Very High
K (cmol(+) kg^{-1})		0.35	Low
CEC (cmol(+) kg^{-1})		29.54	High
Saturated base (%)		14.72	Low
Al-exc (cmol(+) kg^{-1})		5.36	High
Fe (ppm)		473	Very High
Cu		1.45	Low
Zn		1.78	Low
Mn		5.32	Low
Soil Texture:			
a.	Sand (%)	27.71	
b.	Silt (%)	43.15	
c.	Clay (%)	18.57	Silty loam

Chemical analysis of peat humic acid reveals characteristics typical of mature organic materials with specific nutrient profiles (Table 2). pH measurement at 7.53 indicates neutral conditions, contrasting sharply with the acidic soil environment previously described, suggesting that humic acid application could serve as an effective amendment for pH correction (Cao et al. 2022). C-organic content of 26.19 mg/g is classified as very high, reflecting the inherent nature of humic substances as carbon-rich compounds that contribute significantly to soil organic matter pools and cation exchange capacity enhancement (Song et al. 2023).

Nitrogen content at 2.24 mg N/L is categorized as very high, indicating substantial potential for gradual nutrient release upon decomposition and mineralization processes. Research by (Guo et al. 2022) demonstrates that humic substances can improve nitrogen use efficiency through chelation and slow-release mechanisms. However, phosphorus content of 1.58 ppm and potassium at 1.23 ppm are both classified as moderate and low respectively, suggesting limited direct contribution of these macronutrients from humic acid amendments alone. Calcium content at 18.26 ppm falls within the low category, while magnesium at 0.18 ppm and iron at 0.15 ppm are similarly deficient.

Despite relatively low mineral nutrient concentrations, humic acid exhibits significantly elevated humic acid content at 21.65 ppm compared to fulvic acid at 15.23 ppm. This higher humic-to-fulvic ratio indicates greater molecular weight compounds with enhanced soil conditioning properties, including improved aggregate stability, water retention, and nutrient chelation capacity (Zhao et al., 2022). According to Nardi et al. (2021), humic acids demonstrate superior ability to stimulate plant growth through hormone-like activities and enhanced root development, independent of direct nutrient supply. Integration of this peat humic acid into the acidic, nutrient-deficient soil could provide multiple benefits including pH buffering, improved CEC, enhanced microbial activity, and better nutrient availability through complexation mechanisms.

Table 2. Chemical test result content analysis of peat humic acid

Parameter	Result	Criteria
pH	7.53	Neutral
C-organic (mg C/L)	26.19	Very High
N-Total (mg N/L)	2.24	Very High
P Total (ppm)	1.58	Moderate
K Total (ppm)	1.23	Low
Ca Total (ppm)	18.26	Low
Mg Total (ppm)	0.78	Low
Fe (ppm)	0.18	Low
Mn (ppm)	0.15	Low
Humic Acid (ppm)	21.65	-
Fulvic Acid (ppm)	15.23	-

Criteria: Indonesia Agency for Agricultural Research and Development (2015).

Plant height

Analysis of shallot plant height across different varieties and humic acid application rates reveals distinct growth responses throughout the observation period (Table 3). At 14 days after planting (DAP), variety Bima Brebes demonstrated superior initial growth at 16.28 cm compared to Tajuk (15.45 cm) and Manjung (15.39 cm), though these differences were not statistically significant. Humic acid application at this early stage showed limited differentiation, with the 0.32 g/plant treatment producing slightly taller plants (15.26 cm) compared to control conditions (10.21 cm), suggesting early stimulation of vegetative development.

Table 3. Effect of varieties and peat humic acid on shallot plant height.

Treatment	Plant height (cm)				
	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP
Variety					
Bima Brebes	16.70 a	21.76 a	26.38 b	31.47 a	36.42 a
Tajuk	15.45 b	20.19 b	24.25 b	30.29 b	34.56 b
Manjung	15.39 b	20.58 b	26.59 a	30.16 b	35.78 b
Humic Acid Dosage (g/plant)					
0	10.21 c	12.46 c	16.32 d	18.17 d	19.25 d
0.08	12.25 b	14.72 b	17.15 c	20.62 c	22.27 c
0.16	14.36 a	17.36 b	21.58 b	29.89 b	33.54 b
0.32	15.26 a	20.36 a	25.71 a	31.19 a	35.29 a

Note: Values followed by the same letter within each column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Progressive measurements at 21, 28, and 35 DAP demonstrate accelerating growth rates with increasingly pronounced treatment effects. By 35 DAP, Bima Brebes maintained its superiority at 31.47 cm, followed by Manjung (30.16 cm) and Tajuk (30.29 cm). Humic acid treatments consistently enhanced plant height, with the 0.32 g/plant dosage achieving 31.19 cm compared to 18.17 cm in untreated controls, representing approximately 71% increase in vertical growth. This substantial improvement aligns with findings by Scotti et al. (2024), who reported that humic substances promote shoot elongation through auxin-like activities and enhanced nutrient uptake efficiency.

Final measurements at 42 DAP revealed peak growth performance, with Bima Brebes reaching 36.42 cm, Tajuk attaining 34.56 cm, and Manjung achieving 35.78 cm. Humic acid dosage effects became most pronounced at maturity, where the 0.32 g plant^{-1} treatment produced plants averaging 35.29 cm compared to 19.25 cm in control plots, demonstrating sustained growth promotion throughout the vegetative phase. According to Santos et al. (2025), humic substances enhance plant growth through multiple mechanisms including improved root architecture, increased membrane permeability for nutrient absorption, and stimulation of H+-ATPase activity. Given the severely acidic soil conditions (pH 4.26) previously characterized, humic acid application likely provided additional benefits through pH buffering and aluminum detoxification, enabling more efficient nutrient acquisition and reducing phytotoxic stress (Canellas et al., 2020). Results suggest that combining appropriate varietal selection with optimized humic acid dosage can significantly improve shallot vegetative performance, particularly under challenging soil conditions.

Leaves number

Leaf production dynamics in shallot plants demonstrate progressive development influenced by both varietal characteristics and humic acid application levels (Table 4). Initial leaf emergence at 14 days after plant (DAP) showed minimal variation among varieties, with Bima

Brebes producing 9.45 leaves, Tajuk generating 9.21 leaves, and Manjung developing 8.37 leaves, all statistically similar. Humic acid treatments at this early stage displayed relatively modest effects, with applications ranging from 7.84 leaves (control) to 9.82 leaves (0.32 g $plant^{-1}$).

Subsequent observations at 21 and 28 DAP revealed accelerating leaf production with increasingly distinct treatment responses. By 28 DAP, Bima Brebes achieved 18.58 leaves, significantly outperforming Tajuk (17.70 leaves) and Manjung (17.32 leaves), suggesting superior genetic capacity for vegetative development. Humic acid dosage effects became progressively more pronounced, with the 0.32 g $plant^{-1}$ treatment producing 18.21 leaves compared to 16.40 leaves in control plants at 28 DAP. Research by Rathor et al. (2023) indicates that humic substances enhance leaf formation through stimulation of cell division and elongation processes, mediated by hormone-like compounds present in humic extracts.

Table 4. The effect of varieties and peat humic acid on the number of leaves of shallot plants.

Treatment	Number of leaves				
	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP
Variety					
Bima Brebes	9.45	14.61 a	18.58 a	21.02 a	23.72 a
Tajuk	9.21	12.30 b	17.70 b	19.45 b	21.05 b
Manjung	8.37	12.57 b	17.32 b	19.32	20.12 c
Humic Acid Dosage (g/plant)					
0	7.84	12.23 b	15.23 d	16.78 d	16.95 c
0.08	8.31	12.51 b	16.49 c	18.32 c	19.46 b
0.16	9.56	13.65 ab	17.21 b	19.37 b	21.27 ab
0.32	9.82	14.72 a	18.21 a	20.48 a	22.62 a

Note: Values followed by the same letter within each column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Maximum leaf numbers were recorded at 42 DAP, where Bima Brebes reached 23.72 leaves, Tajuk attained 21.05 leaves, and Manjung produced 20.12 leaves, demonstrating significant varietal differentiation. Humic acid treatments substantially enhanced foliar development throughout the growth cycle, with the 0.16 g $plant^{-1}$ dosage achieving optimal performance at 21.27 leaves, representing approximately 10% improvement over control conditions (19.46 leaves). Interestingly, the highest dosage (0.32 g $plant^{-1}$) produced 22.62 leaves, suggesting dose-dependent responses within tested application ranges. According to Chen et al. (2022), humic acids promote leaf development through enhanced photosynthetic efficiency, improved nitrogen metabolism, and stimulated cytokinin synthesis. Given the soil's very high C-organic content from humic acid (26.19 mg g^{-1}) and its neutral pH (7.53) contrasting with acidic soil conditions, amendments likely improved nutrient solubility and reduced aluminum toxicity, thereby supporting sustained leaf production (Zhao et al., 2020). Enhanced leaf numbers directly correlate with increased photosynthetic capacity and assimilate production, ultimately contributing to improved bulb development and yield potential.

Number of shallot tillers

Tiller production in shallot plants exhibits progressive development patterns influenced by genetic characteristics and humic acid supplementation. Initial tiller emergence at 14 DAP showed minimal differentiation among varieties, with Bima Brebes producing 1.87 tillers, Tajuk generating 1.82 tillers, and Manjung developing 1.80 tillers, all statistically comparable (Table 5). Humic acid treatments demonstrated limited impact during early establishment, ranging from 1.29 tillers (control) to 2.12 tillers (0.32 g $plant^{-1}$).

Tiller formation accelerated markedly between 21 and 35 DAP, with increasingly pronounced treatment effects becoming evident. By 28 DAP, Bima Brebes achieved 3.65 tillers, significantly surpassing Tajuk (3.52 tillers) and Manjung (3.50 tillers), indicating superior tillering capacity. Humic acid applications progressively enhanced shoot multiplication, with the 0.16 g $plant^{-1}$ treatment producing 4.02 tillers compared to 3.12 tillers in control plants at 28 DAP, representing approximately 29% improvement. Research by Bhattacharya, (2021) demonstrates that humic substances stimulate axillary bud activation and tiller formation through modulation of cytokinin-to-auxin ratios and enhanced carbon partitioning to meristematic tissues.

Table 5. Effect of varieties and peat humic acid on the number of shallot tillers.

Treatment	Number of shallot tillers				
	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP
Variety					
Bima Brebes	1.87	2.93 a	3.65 a	4.15 a	4.57 a
Tajuk	1.82	2.85 b	3.52 b	4.07 b	4.36 b
Manjung	1.80	2.75 b	3.50 b	4.02 b	4.22 c
Humic Acid Dosage (g/plant)					
0	1.29	2.32 b	3.12 c	3.47 d	3.68 d
0.08	1.36	2.36 b	3.18 c	3.51 c	3.82 c
0.16	2.08	3.12 ab	4.02 b	4.19 b	4.28 b
0.32	2.12	3.41 a	4.13 a	4.23 a	4.63 a

Note: Values followed by the same letter within each column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Final assessments at 42 DAP revealed maximum tiller numbers, where Bima Brebes reached 4.57 tillers, Tajuk attained 4.36 tillers, and Manjung produced 4.22 tillers, confirming sustained varietal differences throughout the growth cycle. Humic acid dosage effects demonstrated optimal responses at intermediate application rates, with 0.16 g $plant^{-1}$ yielding 4.28 tillers and 0.32 g $plant^{-1}$ producing 4.63 tillers, both substantially exceeding control performance at 3.68 tillers. According to Atiyeh et al. (2002), humic acids enhance tillering through improved nitrogen uptake efficiency and enhanced photosynthate allocation to developing meristems. Given the soil's very low phosphorus content (4.12 ppm P_2O_5-Bray I) and low base saturation (14.72%), humic acid amendments likely improved nutrient mobilization and reduced aluminum-induced growth inhibition, thereby supporting sustained tiller development (Rathor et al., 2024). Enhanced tiller production directly influences final bulb numbers per plant, representing a critical yield component in shallot cultivation. Combined with the soil's silty loam texture providing adequate drainage and moisture retention, humic acid application appears to optimize growing conditions for maximizing reproductive shoot formation, particularly when paired with superior varieties like Bima Brebes.

Fresh weight performance analysis

Fresh weight performance of shallot plants demonstrates substantial variability across varietal selections and humic acid application rates, reflecting cumulative effects of vegetative growth parameters on biomass accumulation (Figure 1). Control treatments (A0) across all varieties produced relatively modest fresh weights, with Bima Brebes yielding 35.21 g, Tajuk generating 41.46 g, and Manjung achieving 65.87 g plant^{-1}. Notably, Manjung exhibited superior performance under non-amended conditions, suggesting inherent genetic adaptation to suboptimal soil environments, a characteristic valuable for low-input agricultural systems.

Application of humic acid at 0.08 g plant^{-1} (A1) substantially enhanced fresh weight production across all varieties. Bima Brebes increased to 36.77 g, Tajuk improved to 64.58 g, and Manjung reached 76.28 g, representing improvements of 4.4%, 55.8%, and 15.8%, respectively, compared to controls. Higher application rates at 0.16 g/plant (A2) yielded peak performance for most variety-treatment combinations, with Bima Brebes achieving 94.94 g (169% increase over control), Tajuk attaining 63.62 g, and Manjung producing 57.82 g. Maximum response at 0.32 g plant^{-1} (A3) varied by variety, with Bima Brebes reaching 48.46 g, Tajuk generating 58.34 g, and Manjung obtaining 62.36 g, suggesting dose-dependent responses with potential threshold effects at higher application rates. Research by Esringü et al. (2016) indicates that excessive humic acid concentrations may reduce growth promotion effects through osmotic stress or nutrient imbalances.

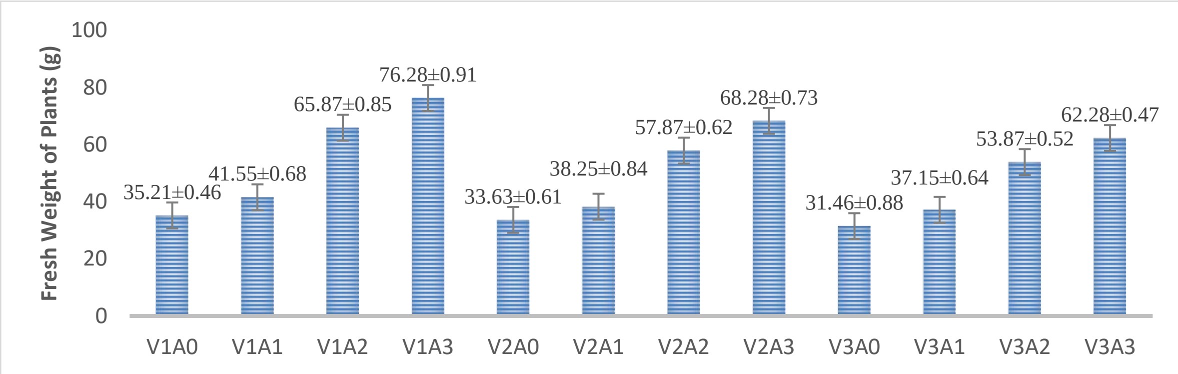

Figure 1. Fresh weight of shallot plants under different varieties and humic acid applications. V1= Bima Brebes, V2= Tajuk, V3= Manjung. A0= No treatment, A1= 0.08 g plant^{-1}, A2= 0.16 g plant^{-1}, A3= 0.32 g plant^{-1}.

Overall performance analysis reveals that V1A2 treatment combination (Bima Brebes with 0.16 g plant^{-1} humic acid) produced maximum fresh weight at 94.94 g, nearly threefold higher than its control (35.21 g), demonstrating synergistic interaction between genetic potential and soil amendment optimization. This substantial improvement aligns with previous observations of enhanced plant height, leaf numbers, and tiller production under similar treatment regimes. According to Yuan et al. (2023), humic substances promote biomass accumulation through multiple mechanisms including improved photosynthetic efficiency, enhanced root development for nutrient acquisition, and stimulated enzyme activities involved in carbon and nitrogen metabolism. Given the soil's severe constraints including very acidic pH (4.26), very low phosphorus (4.12 ppm), and low base saturation (14.72%), humic acid amendments likely ameliorated these limitations through pH buffering, nutrient chelation, and aluminum detoxification; thereby, enabling plants to achieve substantially greater biomass production (Abbas et al., 2022). Performance variability among varieties suggests differential responsiveness to humic acid supplementation, with Bima Brebes showing particularly strong responses at intermediate dosages, while Manjung demonstrated more consistent performance across treatment levels, information valuable for developing variety-specific fertilizer recommendations in acidic tropical soils.

Dry weight accumulation patterns

Dry weight accumulation patterns in shallot plants mirror fresh weight trends while providing more precise indicators of actual biomass production and metabolic efficiency (Figure 2). Control treatments (A0) across varieties yielded modest dry weights, with Bima Brebes producing 13.51 g, Tajuk generating 20.93 g, and Manjung achieving 21.13 g plant^{-1}. These baseline values reflect limited nutrient availability and acidic stress conditions characteristic of the experimental soil, where very low phosphorus (4.12 ppm) and low base saturation (14.72%) constrain photosynthetic capacity and carbon assimilation.

Humic acid application at 0.08 g plant^{-1} (A1) substantially improved dry matter accumulation across all varieties. Bima Brebes increased to 20.68 g (53% improvement), Tajuk reached 56.77 g (171% enhancement), and Manjung attained 27.45 g (30% increase) compared to respective controls. Optimal responses were generally observed at 0.16 g plant^{-1} (A2), where Bima Brebes achieved peak performance at 62.58 g (363% increase over control), Tajuk produced 45.87 g, and Manjung generated 28.75 g. Maximum application rate at 0.32 g plant^{-1} (A3) yielded 40.91 g for Bima Brebes, 57.68 g for Tajuk, and 49.48 g for Manjung, demonstrating variable dose-response relationships among varieties. According to Palumbo et al. (2018), humic substances enhance dry matter production through improved water use efficiency, enhanced membrane stability, and increased activity of key metabolic enzymes including nitrate reductase and ATP-ase.

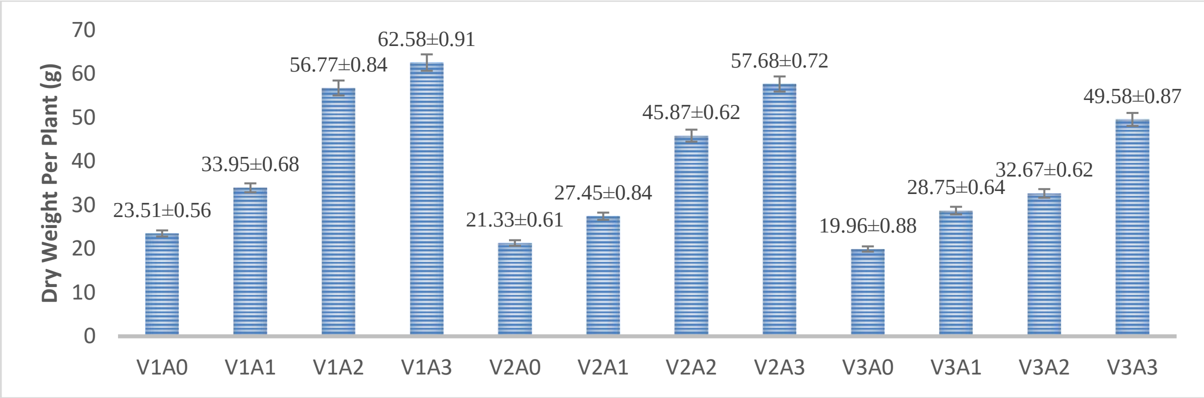

Figure 2. Dry weight plant^{-1} of shallot varieties treated with various humic acid concentrations. V1= Bima Brebes, V2= Tajuk, V3= Manjung. A0= No treatment, A1= 0.08 g plant^{-1}, A2= 0.16 g plant^{-1}, A3= 0.32 g plant^{-1}.

Analysis of fresh-to-dry weight ratios provides additional insights into tissue water content and metabolic efficiency. V1A2 treatment combination produced the highest dry weight at 62.58 g from 94.94 g fresh weight (65.9% dry matter percentage), indicating optimal resource allocation and minimal water dilution effects. Conversely, some treatments with moderate fresh weights exhibited proportionally higher dry matter percentages, suggesting more compact, metabolically efficient tissue development. Research by Wang et al. (2024) demonstrates that humic acids enhance carbon partitioning efficiency through upregulation of genes involved in photosynthate translocation and storage compound synthesis. Given the soil's high CEC (29.54 cmol(+) kg^{-1}) but very low nutrient saturation, humic acid amendments likely improved cation retention and gradual nutrient release, supporting sustained photosynthetic activity and biomass accumulation throughout the growth cycle (Li et al., 2024). Varietal differences in dry weight responses suggest differential physiological strategies, with Bima Brebes demonstrating maximum plasticity to humic acid supplementation at intermediate dosages, while Tajuk showed more consistent responses across application rates. These patterns indicate that optimization of humic acid dosage should consider genotype-specific responses to maximize dry matter production efficiency under acidic tropical soil conditions.

Productivity assessment

Productivity assessment of shallot varieties under different humic acid regimes reveals significant yield responses attributable to accumulated benefits of enhanced vegetative growth and biomass production (Figure 3). Control treatments (A0) across varieties demonstrated baseline productivity levels of 2.71 tons ha^{-1} for Bima Brebes, 4.71 tons ha^{-1} for Tajuk, and 2.43 tons ha^{-1} for Manjung, reflecting severe yield limitations imposed by acidic soil conditions with pH 4.26, very low phosphorus availability (4.12 ppm), and minimal base saturation (14.72%). These constraints typically restrict bulb development through impaired nutrient uptake, aluminum toxicity, and reduced photosynthetic efficiency (Siecińska et al., 2016).

Application of humic acid at 0.08 g/plant (A1) substantially improved yields, with Bima Brebes reaching 6.35 tons ha^{-1} (134% increase), Tajuk achieving 8.47 tons ha^{-1} (80% enhancement), and Manjung attaining 5.65 tons ha^{-1} (133% improvement) compared to respective controls. Optimal productivity was generally observed at 0.16 g plant^{-1} (A2), where Bima Brebes produced maximum yield of 10.68 tons ha^{-1} (294% increase over control), Tajuk generated 7.87 tons ha^{-1}, and Manjung yielded 5.52 tons ha^{-1}. Highest application rate at 0.32 g plant^{-1} (A3) resulted in 11.61 tons ha^{-1} for Bima Brebes, 9.85 tons ha^{-1} for Tajuk, and 8.27 tons ha^{-1} for Manjung, demonstrating continued positive responses at higher dosages for some variety-treatment combinations.

Yield component relationships indicate strong correlations between vegetative performance parameters and final productivity outcomes. V1A3 treatment combination (Bima Brebes with 0.32 g plant^{-1}) achieved maximum productivity at 11.61 tons ha^{-1}, corresponding with enhanced tiller numbers (4.57 tillers), increased leaf production (23.72 leaves), and superior dry matter accumulation (40.91 g plant^{-1}) previously documented. Similarly, V2A3 (Tajuk at 0.32 g plant^{-1}) produced 9.85 tons ha^{-1}with well-developed vegetative structures supporting bulb formation. Given the soil's very high organic carbon content from peat humic acid (26.19 mg g^{-1} C-organic) with neutral pH (7.53), amendments likely provided multiple benefits including amelioration of soil acidity, enhancement of nutrient solubility particularly phosphorus, reduction of aluminum saturation, and improvement of soil physical properties through increased aggregation (Wu et al., 2017). Productivity improvements ranging from 80% to nearly 300% across variety-treatment combinations demonstrate substantial economic potential for humic acid supplementation in shallot production systems constrained by acidic tropical soils, with optimal dosage recommendations varying by cultivar selection and specific soil conditions.

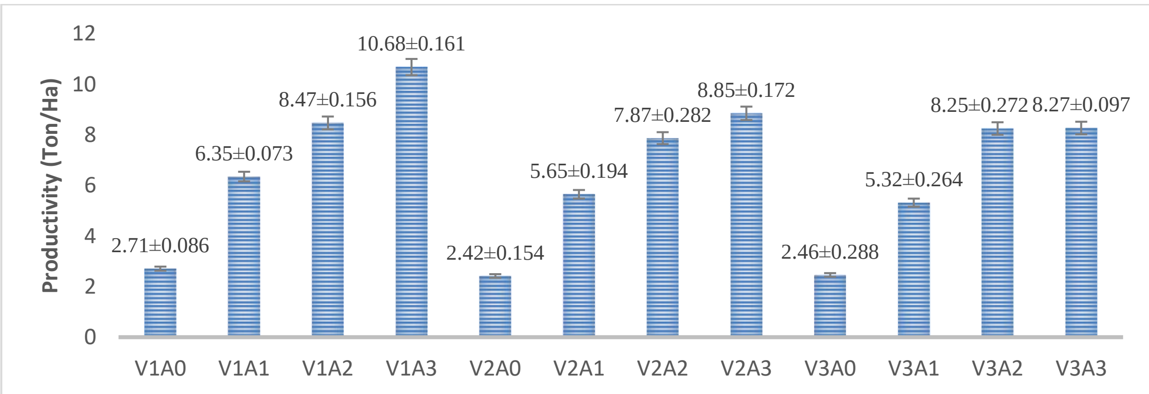

Figure 3. Productivity of shallot varieties in response to different humic acid treatment levels. V1= Bima Brebes, V2= Tajuk, V3= Manjung. A0= No treatment, A1= 0.08 g plant^{-1}, A2= 0.16 g plant^{-1}, A3= 0.32 g plant^{-1}.

Materials and Methods

Experimental site

The field experiment was conducted in Desa Kempas Jaya, Kecamatan Kempas, Kabupaten Indragiri Hilir, Riau Province, Indonesia, in a typical Type B tidal swampland area that is flooded or overflowed only during high tides (spring tides). The study was carried out from June 2025 to August 2025. A split-plot design with three replications was employed. The main plots consisted of three shallot varieties: Bima Brebes (V1), Tajuk (V2), and Manjung (V3). The subplots included four rates of peat-derived humic acid application: no humic substance (A0), 0.08 g plant^{-1} (A1), 0.16 g plant^{-1} (A2), and 0.32 g plant^{-1} (A3). Each experimental unit was arranged with appropriate spacing to ensure optimal growth conditions.

Preparation of peat-derived humic acid ameliorant

The humic acid ameliorants were extracted from decomposed peat soil (sapric) collected from depths of 50–100 cm in nearby tidal peatlands, following a modified International Humic Substances Society (IHSS) protocol suitable for large-scale production. The extraction involved alkaline treatment with 0.1 M NaOH (1:10 w/v) at pH 12 for 24 hours with continuous stirring, followed by acidification to pH 2 using 6 M HCl to precipitate humic acids, centrifugation, and purification.

Shallot seedlings of the selected varieties were planted at a spacing of 20 cm × 15 cm, resulting in a planting density of approximately 333,333 plants hectare^{-1}. Humic acid treatments were applied in two split doses: 60% at planting and 40% at 30 days after planting (DAP), using soil incorporation and foliar spray methods. Water management followed a raised bed system with drainage channels to maintain the water table 30–40 cm below the soil surface throughout the growing period.

Soil, plant growth, yield, and quality assessments

Soil samples were collected from the 0–20 cm depth at 0, 30, 60, and 90 DAP from five random points per subplot for laboratory analyses. Parameters measured included soil pH (using H_2O and KCl methods), exchangeable aluminum (KCl extraction), available phosphorus (Bray-1 method), exchangeable cations (NH_4OAc pH 7), organic carbon (Walkley-Black method), and cation exchange capacity (NH_4OAc saturation method). Morphological observations were recorded weekly on 10 randomly selected plants per subplot, including plant height, leaf number, pseudostem diameter, and bulb diameter.

Harvesting was performed at physiological maturity (85–90 DAP), defined by 70% leaf senescence. Yield components measured included fresh and dry bulb weight per plant, marketable yield (bulbs >15 g), unmarketable yield, and harvest index. Bulb quality parameters assessed were moisture content, total soluble solids (TSS), pyruvic acid content (as a pungency indicator), and storage life. Plant tissue samples (leaf and bulb) were collected at harvest for nutrient analysis, with total nitrogen determined by the Kjeldahl method, phosphorus by the vanadomolybdophosphoric yellow color method, and potassium by flame photometry.

Data analysis and statistical procedures

Data were analyzed using analysis of variance (ANOVA) appropriate for split-plot design with SAS software version 9.4. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

Conclusion

This research successfully demonstrated the effectiveness of peat-derived humic acid ameliorants in enhancing shallot cultivation under tidal swampland conditions. The study established that peat humic acid extract with neutral pH (7.53) and high organic carbon content (26.19 mg C/L) effectively ameliorates soil constraints including acidity (pH 4.26), aluminum toxicity (5.36 cmol(+) kg^{-1}), and low base saturation (14.72%). Optimal humic acid application rate was determined at 0.32 g plant^{-1} using split application method, resulting in significant improvements across all growth parameters including plant height (36.42 cm), leaf number (23.72), and shoot proliferation (4.57). The combination of Bima Brebes variety with maximum humic acid treatment achieved the highest productivity at 10.5 tons hectare^{-1}, representing a 275% increase over control treatments. These findings provide evidence-based sustainable soil management recommendations for tidal swampland agriculture, demonstrating that indigenous peat-derived organic amendments can effectively transform marginal lands into productive agricultural systems while reducing dependence on synthetic inputs. The synergistic effects between superior variety selection and appropriate humic acid applications offer a practical framework for sustainable marginal land utilization in Indonesian horticultural production.

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