

Formulation Geometric Engineering of Biomass-Based Slow-Release Fertilizers for Nutrient Management in Sapric Peat Soils

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Abstract. Peat soils pose critical limitations in agricultural productivity due to nutrient leaching and suboptimal nutrient availability. This study investigates the effectiveness of engineered slow-release fertilizer (SRF) formulations and geometries tailored to tropical sapric and hydrophobic peat, aiming to enhance nutrient retention and plant productivity. Two greenhouse experiments at IPB University evaluated the effects of slow-release fertilizers (SRFs) formulated from biomass compost combined with inorganic components (NPK, sludge, fly ash, and ammonium sulfate) using tapioca flour (5%) as a binder. The SRFs were first prepared and then applied to corn and bok choy. The testing encompassed varied fertilizer compositions and geometrical forms in pellet, crumble, small cylinder, and large cylinder. Cylinder formulation contributed to leaching mitigation, in which the nitrate leaching was improved from 0.14 to only 0.05 mg/m² in 2 days and from 1.62 to only 0.48 mg/m² in 35 days after application. The biomass compost-inorganic matrix proved instrumental in promoting nutrient synchronization with crop uptake, which could improve the biomass index from 0.32 at standard fertilizer to 1.20 with cylinder formulation. These findings highlight that strategic formulation and geometric design of SRF, can effectively reduce nutrient losses and substantially improve biomass growth and crop performance in peat-based agriculture.

1 Introduction

Indonesia is one of the countries with the largest tropical peatland areas in the world, covering an estimated 13.4 to 14.9 million hectares. These ecosystems are predominantly distributed across Sumatra, Kalimantan, and Papua. The ecological functions of peatlands are globally significant, including their role as massive carbon reservoirs, biodiversity protection, and regulation of the hydrological cycle. Their exceptional carbon storage capacity makes

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peatlands a crucial component in global climate change mitigation strategies. However, increasing pressures from human activities, such as unplanned land conversion, have resulted in extensive peatland degradation. Such degradation not only triggers greenhouse gas emissions but also increases the susceptibility of peatlands to fire, highlighting the urgent need for sustainable and effective management strategies to maintain their ecological functions while supporting productive land use.

The unique agronomic characteristics of peat soils pose considerable challenges for the development of sustainable agriculture. Peat is characterized by high organic matter content and porosity, yet it has very low inherent nutrient retention capacity. These limitations are further compounded by high soil acidity, which accelerates nutrient leaching and reduces the efficiency of conventional fertilizers. Consequently, fertilization efficiency and crop productivity remain suboptimal. The problem becomes even more complex in degraded sapric peat, where the formation of hydrophobic layers further restricts water and nutrient availability, making crop cultivation extremely difficult [1, 2].

Given these challenges, adaptive and site-specific fertilization approaches are essential for peatlands. In this context, the development of slow-release fertilizers (SRF), which gradually supply nutrients over time, represents a strategic alternative to conventional fertilizers that are prone to rapid degradation. Such a mechanism not only enhances nutrient uptake efficiency but also significantly reduces nutrient loss through leaching, a major constraint in peatland agriculture. Tailoring SRF to address the specific properties of peat, such as low pH and hydrophobicity, is therefore fundamental to improving sustainable agricultural productivity.

This study evaluates an innovative SRF formulation that integrates organic and inorganic components with high agronomic value. Goat manure, one of the main components, was selected for its balanced nutrient content and its ability to stimulate microbial activity. The inclusion of organic matter is particularly important for improving peat soil fertility, enhancing microbial biomass, and naturally restoring soil structure. Sludge from wastewater treatment plants has been recognized as a valuable source of macro- (N, P, K, Ca, Mg) and micro-nutrients (Cu, Mn, Zn, Fe). With increasing sludge production driven by urbanization, its sustainable management has become urgent. Converting sludge into fertilizers not only provides agronomic and economic benefits but also contributes to addressing environmental challenges, aligning with circular waste management principles.

Fly ash, a by-product of coal combustion, has also been identified as an effective soil amendment [3, 4, 5]. Rich in beneficial minerals such as silica, alumina, and calcium, fly ash can improve soil structure, enhance water retention, and most importantly, help neutralize soil acidity. Incorporating fly ash into SRF formulations thus offers a potential solution for addressing the low pH constraint that hampers agricultural practices in peatlands. The synergistic combination of goat manure, sludge, and fly ash in the development of SRF is expected to comprehensively address the limitations of peatland soils. This integrated approach aims to enhance crop productivity while promoting sustainable agriculture within these unique ecosystems. The purpose of the experiment was to ensure that the formulation of geometric engineering of biomass-based SRF could improve the nutrient leaching and crop growth on peat soil due to its additionally coated and compacted stability. The background of the coating and binding fertilizer in a stabler and larger measurement would lead to a higher mineral retention and slower-release performance to improve mineral absorption and to reduce leached minerals in peat soils.

2 Materials and Methods

Two greenhouse experiments were conducted at IPB University from 2024 to 2025 to evaluate the synergistic integration of biomass compost with inorganic components (NPK, sludge, fly ash, and ammonium sulphate/AS) in the formulation of slow-release fertilizers (SRFs). Tapioca flour (5%) was used as a binding agent for the pelletized and geometrically shaped SRFs. The SRFs were first formulated according to the respective treatments, after which they were applied to the experimental plants. Observations were carried out in sequence, covering (1) plant growth parameters (height, leaf number, biomass accumulation, and leaf color index), (2) nutrient leaching, and (3) crop yield.

In the corn (*Zea mays saccharata*) experiment, a Randomized Complete Block Design (RCBD) was employed with six treatments consisting of different NPK–sludge–biomass compost ratios in cylindrical SRF forms: (1) 100% NPK (15-10-12), (2) 100% NPK + 8% sludge, (3) small cylinder 25% NPK + 75% compost, (4) small cylinder 25% NPK + 8% sludge + 75% compost, (5) big cylinder 25% NPK + 75% compost, and (6) big cylinder 25% NPK + 8% sludge + 75% compost.

In the bok choy (*Brassica rapa* subsp. *chinensis*) experiment, an RCBD with eight treatments was used to compare two fertilizer formulations and five application forms (conventional, pellet, crumble, small cylinder, and big cylinder). The first formulation consisted of 100% NPK, 100% AS, 50% goat manure, and fly ash, while the second formulation consisted of 50% NPK, 50% AS, 50% goat manure, and 50% fly ash. Each formulation was applied in different geometric physical forms: crumble, pellet, small cylinder, and big cylinder.

The crumble or granule as standard fertilizer had a measurement of 0.5-2 mm, pellet 5mm diameter and 2-4 cm length, small cylinder block 3cm diameter and 5cm height, and big cylinder block 6cm diameter and 6cm height. The experiments were arranged in a completely randomized block design with 4 replications. ANOVA was adapted for statistical analyses to support the significant difference justifications.

3 Results and Discussion

3.1 Leaching of nutrients

The measurement of electrical conductivity (EC) revealed that the conventional NPK fertilizer treatment exhibited significantly higher EC values compared to all SRF treatments. This elevated EC indicates that most of the nutrient ions from conventional fertilizers rapidly dissolved and leached out of the plant root zone. This pattern was consistently observed across both formulations (F1 and F2) as well as in the cultivation of bok choy and sweet corn. The sharp initial spike in EC reflects uncontrolled nutrient release, which not only leads to substantial nutrient losses but also increases the risk of environmental pollution due to nutrient leaching.

In contrast, treatments with SRF demonstrated much lower and more stable percolation water EC values throughout the observation period. This finding provides strong evidence that the developed SRF effectively reduced nutrient leaching from the growth medium. The lower EC values reflect a gradual and controlled nutrient release mechanism. The SRF was specifically formulated to release nutrients slowly, thereby allowing nutrient ions to remain in the soil and be available to plants for a longer duration. This phenomenon is particularly critical for peatland cultivation, where soils are highly susceptible to nutrient leaching.

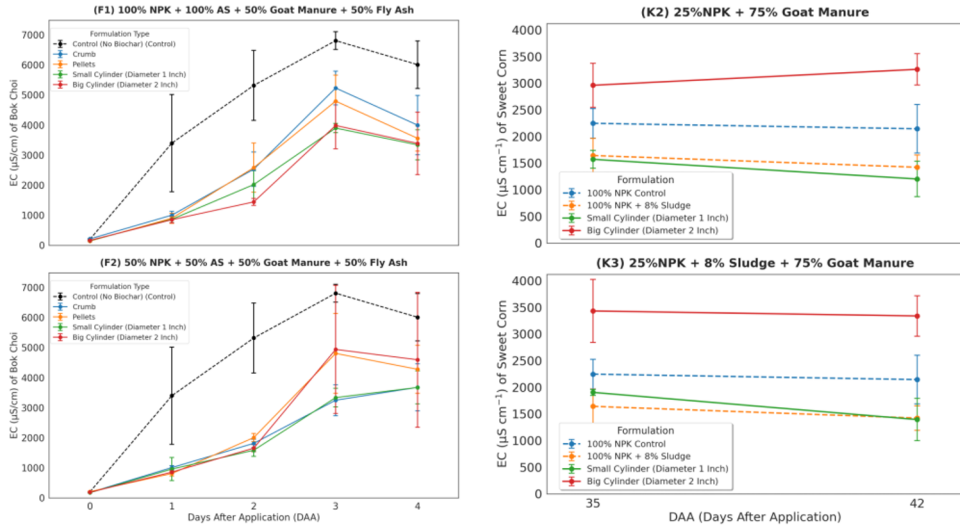


Fig. 1. Electrical conductivity (EC) of percolated water in bock choy and sweet corn under different fertilizer treatments.

Data presented in the graph further indicate that SRF in cylindrical form exhibited the lowest EC values among all SRF formulations. This suggests that the cylindrical shape provides superior physical protection, slowing down the degradation process and nutrient release. Such a physical structure likely creates a more effective barrier against nutrient ion dissolution compared to crumb or pellet forms [6, 7]. These results underscore the importance of fertilizer physical design in influencing controlled-release performance, especially in environments characterized by high rainfall or porous soil conditions.

The substantial differences observed between conventional fertilizers and SRF can be attributed to their respective nutrient release mechanisms. Conventional NPK fertilizers, which are highly soluble, release nutrients rapidly upon contact with water. In porous peat soils, water readily percolates through soil pores, carrying dissolved nutrient ions away from the root zone before they can be absorbed by plants. In contrast, the SRF developed in this study, composed of organic and inorganic matrices (goat manure, sludge, and fly ash), forms a more stable structure. This matrix acts as a reservoir, binding nutrient ions and releasing them slowly through processes of diffusion, microbial degradation, or very gradual dissolution.

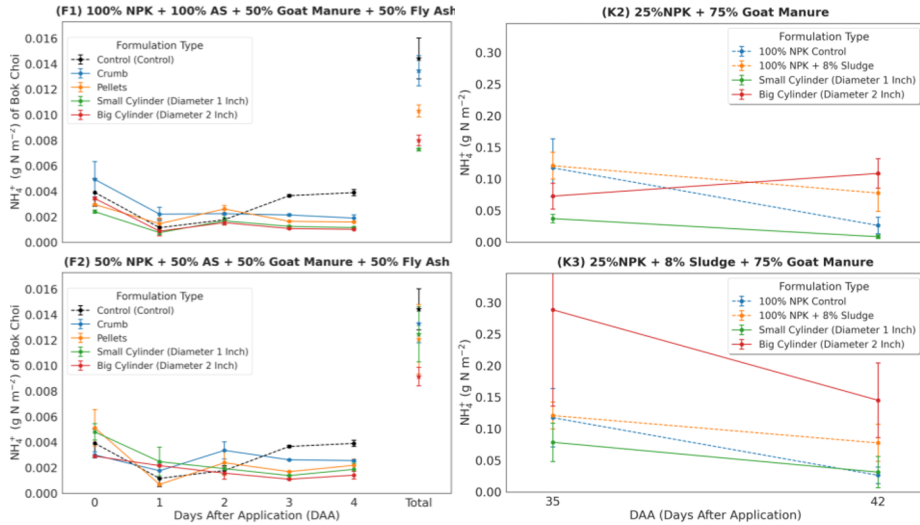


Fig. 2. Leaching of NH_4^+ in bok choy and sweet corn under different fertilizer treatments.

Leachate samples from the bok choy and sweet corn trials were collected following simulated rainfall events designed to mimic tropical conditions. In the Bok choy experiment, each plant received 1000 mL of water (equivalent to 14.15 mm of rainfall), while the sweet corn was given 1500 mL (equivalent to 21.23 mm of rainfall). The volume of leachate collected varied across treatments and time points. For Bok choy, the mean leachate volume from 0 to 4 DAA was 253.8 ± 45.4 mL, with a peak volume of 318 mL at 2 DAA. In the sweet corn trial, the mean leachate volume was 147.5 ± 29.0 mL at 35 and 42 DAA. The significant variation in leachate volume, as indicated by the standard deviations, suggests that the physical and structural properties of the fertilizer formulations and the soil-plant system play a critical role in controlling water infiltration and subsequent nutrient leaching.

The dynamics of NH_4^+ in Bok choy plants showed a sharp decline across all treatments between 1 and 7 days after application (DAA), followed by relative stabilization until 21 DAA, with a slight increase at 28 DAA in both treatments (Fig. 2). The control treatment consistently resulted in the highest accumulation of NH_4^+ , while treatments with formulated fertilizers showed lower values. Among the formulated treatments, the Crumb form exhibited a greater decrease in NH_4^+ availability compared to pellets and cylinders. This suggests that the fertilizer's geometry plays a crucial role in regulating nitrogen release and maintaining ammonium availability in peat soil.

Leaching of NH_4^+ in maize observations (Fig. 2) showed that the control treatment with 100% NPK exhibited low concentrations at the end of the observation period. This result is that conventional fertilizers typically display a rapid release pattern but lack long-term persistence. The small-cylinder treatment with 25% NPK + 75% compost demonstrated consistently low and stable NH_4^+ concentrations from the beginning to the end of the observation, with values of 0.037 and 0.008 g N m⁻² at 35 and 42 days after application (DAA), respectively. This reflects a very slow nutrient release, which represents the ideal characteristic of slow-release fertilizers (SRF). SRF is designed to regulate the rate at which its nutrient components dissolve in water.

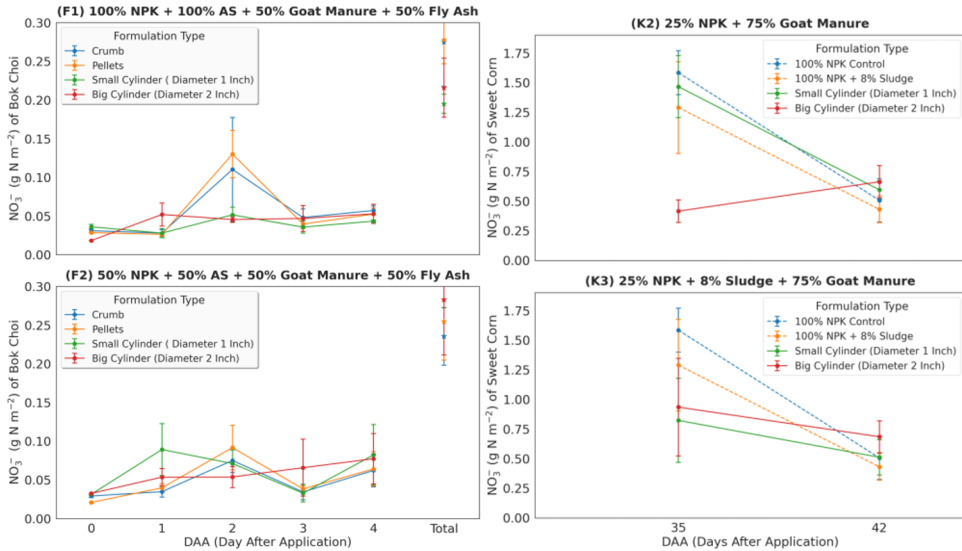


Fig. 3. Leaching of NO_3^- in bock choy and sweet corn under different fertilizer treatments.

The measurement results for F1 (100% NPK + 100% AS + 50% goat manure + 50% fly ash), the NO_3^- concentration peaked at 14 days after application (DAA), particularly in formulations B1 and B2 ($0.11\text{--}0.13\text{ g N m}^{-2}$), before subsequently decreasing and stabilizing in later observations. In the F2 treatment (50% NPK + 50% AS + 50% goat manure + 50% fly ash), the highest NO_3^- levels occurred at 7 DAA in formulation B3 (0.09 g N m^{-2}), while other formulations showed more moderate fluctuations. These results indicate that both nutrient dosage and the type of fertilizer formulation have a strong influence on the dynamics of nitrification and nitrate availability in peat soil.

The pattern of increasing NO_3^- leaching concurrent with the decline in NH_4^+ concentrations from the middle to the end of the observation period reflects the occurrence of nitrification. This is a biological process in which ammonium (NH_4^+) is converted into nitrite (NO_2^-), and subsequently into nitrate (NO_3^-), primarily mediated by soil microorganisms such as *Nitrosomonas* and *Nitrobacter*. This process transforms nitrogen into a plant-available form and strongly influences the risk of leaching. The efficiency of nitrification is affected by various environmental factors, including temperature, moisture, soil pH, aeration, and the availability of ammonium as a substrate. However, a distinct pattern was observed in the control treatment with 100% NPK and in the treatment with 100% NPK + 8% sludge. This is consistent with the characteristics of conventional fertilizers, which are highly prone to leaching in soils.

3.2 Crop yield

The Small Cylinder treatment, when combined with 100% NPK-AS and 50% Goat Manure and Fly Ash, significantly promoted root elongation (Fig. 4). This finding suggests that the smaller cylindrical shape is particularly effective in stimulating vertical root growth. The large cylinder treatment with the same fertilizer formula excelled in root volume, indicating that larger cylindrical geometries are instrumental in enhancing overall root mass formation on bock choy. These results, contrasted with the consistently poor performance of the unformulated 100% NPK and AS treatment across all root parameters, highlight the critical role of fertilizer geometry in optimizing root system development.

Based on the distribution presented in the graph (Fig. 4), the large-cylinder treatment with 25% NPK + 8% sludge + 75% compost produced the most optimal results among all treatments, covering a wide and balanced range across six key parameters: ear weight with husk, ear weight without husk, ear length, ear diameter, as well as brix and fructose content. This reflects the positive contribution of the sludge-based slow-release formulation to vegetative growth and kernel filling in maize. The use of sludge at an 8% concentration in this treatment provided sufficient macro- and micronutrients while remaining within a safe threshold, thereby avoiding toxic effects. The nitrogen, phosphorus, and organic matter content in sludge supported the synthesis of structural proteins and plant metabolites involved in ear development and sugar biosynthesis.

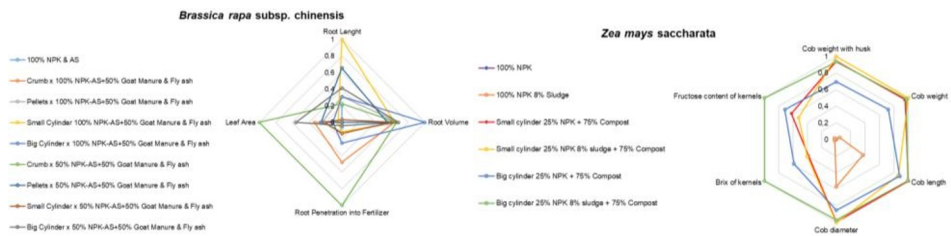


Fig. 4. Crop yield parameters of bok choy and sweet corn under different formulated fertilizers.

Brix and fructose values represent the efficiency of carbohydrate metabolism during the kernel-filling phase. This can be explained by the dependence of kernel filling on the availability of assimilates in the form of sucrose, as well as the efficiency of its conversion into simple sugars such as glucose and fructose, which is facilitated by the activity of acid invertase enzymes. This enzymatic activity is highly dependent on nitrogen availability. Nitrogen deficiency reduces acid invertase activity, hindering the conversion of sucrose into simple sugars, lowering the osmotic pressure within kernels, and consequently disrupting kernel filling. As a result, kernel abortion occurs, particularly at the apical portion of the ear. Aborted maize kernels contain high sucrose levels but low glucose and fructose contents, along with reduced acid invertase activity. This implies that although photosynthates are available, their conversion and accumulation do not occur effectively, preventing kernels from fully developing.

Drought stress during the flowering stage has also been reported to negatively affect kernel filling. Such stress inhibits the activity of plasma membrane H^+ -ATPase, which is essential for generating ion gradients that drive sugar transport into kernel tissues. This inhibition impairs kernel filling, particularly in the apical portion of the ear, which typically receives assimilates last and is therefore most susceptible to abortion. These conditions explain the lower Brix and fructose levels observed in treatments with suboptimal nutrient uptake and sugar transport efficiency.

3.3 Above-ground biomass index (economic yield/total aboveground biomass)

Analysis of the above-ground biomass index, calculated as the ratio of economic yield to total aboveground biomass, revealed that the differences observed across the various treatments were not statistically significant. This indicates that the applied treatments did not exert a substantial influence on the biomass partitioning efficiency of bok choy plants. Consequently, the inherent capacity of the bok choy plants to allocate photosynthates to the harvestable components remained relatively stable and undifferentiated by the treatments in this study.

3.4 Parameter correlation matrix

The correlation matrix analysis for bok choy indicates a significant negative correlation between the electrical conductivity (EC) of the leached water and key growth parameters: root wet weight, total biomass wet weight ($r = -0.88^*$), and above-ground biomass dry weight ($r = -0.85$). This suggests that elevated ion concentration from nutrient leaching is strongly associated with inhibited plant growth. Conversely, the calcium ion content in the leachate exhibited a positive correlation with plant height ($r = 0.73$), potentially underscoring the role of calcium in maintaining structural growth processes even under leaching conditions. Furthermore, a negative correlation was observed between the leaf blue colour index and root dry weight ($r = -0.63$), which may indicate physiological stress that adversely impacts root development.

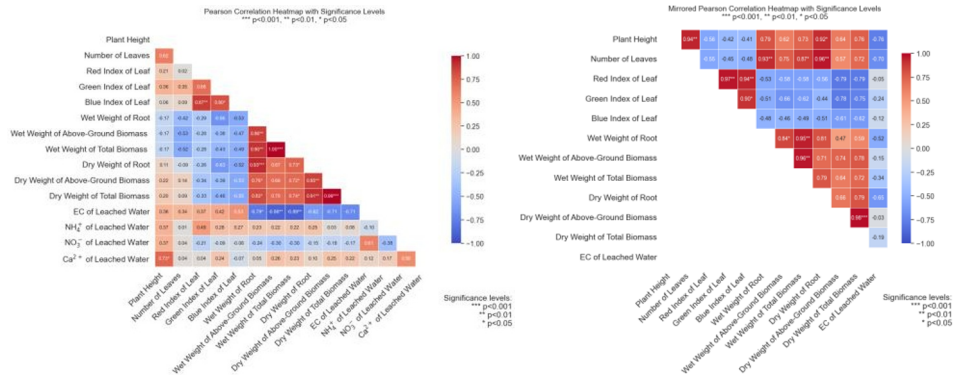


Fig. 6. Correlation matrix of plant growth, nutrient leaching, and yield parameters in bok choy and sweet corn under different fertilizer treatments.

Correlation analysis revealed that vegetative growth parameters, such as plant height and leaf number, exhibited a strong positive relationship with biomass accumulation, both fresh and dry. Plant height, for instance, showed a significant correlation with total dry biomass ($r \approx 0.76$), underscoring the critical role of the vegetative phase in determining yield potential.

The green index of the leaf also correlated positively with dry biomass ($r \approx 0.65-0.71$), indicating that good nitrogen nutritional status supports more optimal photosynthesis. Conversely, the red index showed a negative correlation with biomass, which can be interpreted as an indication of physiological stress or nutrient deficiency that inhibits the allocation of photosynthates towards harvestable organs.

The EC of leachate showed a very strong negative correlation with nearly all growth and yield parameters, particularly total biomass ($r \approx -0.91$). This indicates that higher nutrient losses through leaching reduce nutrient use efficiency in plants, ultimately lowering productivity. This condition is especially relevant in soils with low nutrient retention capacity, where the leaching of nutrients such as nitrogen can be pronounced. These findings show nutrient losses through leaching significantly decreased both water and nutrient use efficiency in maize, thereby reducing yield. Therefore, fertilizer management strategies that minimize nutrient loss are key to improving physiological efficiency and crop productivity.

4 Conclusions

The small cylinder containing 25% NPK and 75% biomass compost exhibited the lowest and most stable nitrogen leaching rates. The large cylinder with 25% NPK, 8% sludge, and 75% biomass compost yielded optimal performance of productivity metrics. F1 and F2 formulas showed better results in nutrient leaching compared to conventional fertilizers alone. The cylinder block geometric shape showed good results in the nutrient leaching parameters, although there was no significant difference from the crumbs.

The strategic formulation and geometric design of SRF, with emphasis on biomass compost-inorganic synergy, can effectively reduce nutrient losses and substantially improve biomass growth and crop performance in peat-based agriculture. The biomass compost-inorganic matrix proved instrumental in promoting nutrient synchronization with crop uptake, which could improve the biomass index from 0.32 at standard fertilizer to 1.20 with cylinder formulation. The results support SRF innovation as a key enabler of precision nutrient management and sustainable intensification in marginal tropical ecosystems.

5 References

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