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Biosurfactant-enriched organic fertilizer as a sustainable strategy to reduce chemical inputs and improve maize performance on Ultisols

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ABSTRACT

The increasing demand for maize in Indonesia is challenged by suboptimal productivity on acidic Ultisols, despite high doses of inorganic fertilizers being applied. This study aimed to evaluate soil pH dynamics and maize response to liquid organic fertilizer (LOF) enriched with *Sapindus rarak* biosurfactants as a substitute for chemical fertilizers. A factorial completely randomized design was used with two factors: inorganic fertilizer (NPK + Urea) doses (0%, 50%, and 100% of the recommended rate) and biosurfactant concentrations (0%, 0.1%, 0.2%, and 0.3%). Data were analysed using the F-test at a 5% significance level, with LSD tests applied for significant effects. Results showed that soil pH in maize crops decreased over time but remained slightly acidic. Higher NPK doses generally increased soil pH, especially at 45 days after planting (DAP). Biosurfactant-enriched LOF significantly impacted leaf area index (LAI), relative growth rate (RGR), and shoot-root ratio, particularly at 60 DAP. The highest maize yield, reaching 6.60 tons per hectare, was obtained with a combination of 50% of the recommended inorganic fertilizer and 50 mL L^{-1} of 0.1% biosurfactant-enriched LOF. This yield is comparable to the normal yield obtained by farmers when applying 100% of the recommended rate of inorganic fertilizer. Optimising fertilizer application and planting strategies to effectively manage the shoot-to-root ratio is essential for improving maize productivity and enhancing resource use efficiency. The study highlights the potential to reduce chemical fertilizer use by up to 50%, lowering costs while improving soil pH and root development. It promotes efficient resource use, supports integrated nutrient management using local materials such as *Sapindus rarak*, and encourages farmer training and sustainable agricultural policies to restore productivity on degraded Ultisols.

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1. INTRODUCTION

The demand for maize is expected to increase year by year in line with the growing population, necessitating efforts to boost maize production. Indonesia still imported up to 20,000 tons of maize in November 2023. The high demand for maize is driven by the increasing needs of the livestock feed and food processing industries (Ariyanto et al., 2023). Maize is generally cultivated in Ultisol soils in Indonesia. Ultisols are mineral soils characterised by acidic reactions, low nutrient content, and high levels of aluminium (Al) and iron (Fe) (Sharma et al., 2025). Ishak et al. (2024) explained that Ultisol soils exhibit various characteristics influenced by factors such as soil compaction and low fertility due to their highly weathered nature, often characterised by high clay content, low pH levels, low nutrient availability, low cation exchange capacity (CEC), and low organic matter content. Moreover, the required dosage of inorganic fertilizers to maximise maize productivity is very high, but it is often ineffective. According to recommendations from the Ministry of Agriculture of the

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Republic of Indonesia (Kementan, 2022), the fertilizer requirement for maize cultivation in Ultisol soils in Pesisir Selatan, West Sumatra, is 350 kg ha^{-1} NPK (15-10-12) and 250 kg ha^{-1} Urea. The high requirement for inorganic fertilizers on Ultisol soils becomes a burden on maize farming costs.

The problem of Ultisols in Indonesia for maize cultivation primarily stems from their inherent soil characteristics, which pose significant challenges for crop growth. Ultisols, covering about 25% of Indonesia's land area, are characterised by low nutrient availability, high acidity, and aluminium saturation, which collectively hinder maize productivity. The following sections detail these issues and potential solutions. Ultisols often lack essential nutrients such as phosphorus (P) and potassium (K), which are critical for maize growth (Fitriatin et al., 2017). The presence of high aluminium levels can be toxic to maize, further complicating nutrient uptake (Murni et al., 2018). With average pH levels below 4.5, the acidity of Ultisols limits the availability of nutrients and affects microbial activity essential for soil health (Jayadi et al., 2023). Site-specific nutrient management (SSNM) has shown promise in improving maize yields by optimising fertilizer application based on local soil conditions (Murni et al., 2018). The use of organic materials such as compost and biochar can enhance soil structure and nutrient availability, mitigating some of the adverse effects of Ultisol characteristics (Fauzan & Arafat, 2023). Despite these challenges, some farmers may struggle to implement these management practices due to economic constraints and limited knowledge, which can perpetuate low productivity in maize cultivation on Ultisols (Jayadi et al., 2023).

A report by Oxford Analytica (2022) noted that the increase in the price of artificial fertilizers over the past three years has been over 100%. According to Gnutzmann and Spiewanowski (2016) and de Oliveira et al. (2023), this increase is driven by rising transportation costs, high demand, and raw materials imported from other countries. Efforts to reduce maize plants' dependence on inorganic fertilizers on Ultisol soils are being made using liquid organic fertilizers derived from *Chromolaena odorata* (LOF) enriched with biosurfactants.

Due to the importance of evaluating the effectiveness of this LOF under various environmental conditions and across different commodities, trials should be conducted on maize crops cultivated in Pesisir Selatan, West Sumatra, particularly those treated with biosurfactants. Jamilah et al. (2020) demonstrated that the application of Crocober LOF on purple rice plants could reduce the use of inorganic fertilizers by up to 30%. This LOF has been tested on several crops, including rice, vegetables, and fruits. However, there is no information on its effectiveness when biosurfactants are added.

Biosurfactants are compounds produced by living organisms such as microbes. The term biosurfactant consists of two words: *bio*, meaning life, and *surfactant*, meaning surface-active agent. Biosurfactants can reduce surface tension and are used in various applications, such as enhancing oil recovery, bioremediation of oil-contaminated sites, and as emulsifiers in the food and cosmetic industries. Biosurfactants have gained attention because they are naturally degradable and have lower toxicity compared to synthetic surfactants (Poomalai et al., 2024). They enhance nutrient absorption capacity on leaf surfaces (Bee et al., 2019). Aryanti et al. (2020) reported that some materials that can be used as surfactants include the lerak fruit (*Sapindus rarak* DC.). Ethanol extract of lerak fruit has high saponin activity with a foam index of 20,000 and a haemolytic index of 2,500 (Novianti et al., 2024; Sari et al., 2024). The main component of lerak is saponin, which functions as a detergent (Aryanti et al., 2021). A report by Zainuddin et al. (2022) showed that the ethanol extract of lerak fruit contains secondary metabolite groups such as alkaloids, saponins, tannins, quinones, steroids/terpenoids, and phenols. The use of biosurfactants is said to enhance the efficiency of LOFs. However, there are no research reports on the utilisation of biosurfactants in LOF for maize plants on marginal lands. The objective was to observe the changes in soil pH dynamics based on plant age and the response of maize crops to LOF enriched with biosurfactants in an effort to substitute artificial chemical fertilizers and to understand the relationship between observation variables and maize crop yields.

2. MATERIALS AND METHODS

This research was conducted on Ultisol soil with a pH of 4.22, in Bayang Subdistrict, Pesisir Selatan Regency (elevation 5 metres above sea level), at a central maize cultivation area. The materials used in this study included Pioner32 (P32) variety seeds, 100 kg ha^{-1} of $Ca(CO_3)_2$, NPK Phonska fertilizer, liquid organic fertilizer, *Sapindus rarak* (lerak fruit), 96% alcohol, and a pH meter.

The research design employed a completely randomised design (CRD) with a factorial arrangement involving two treatment factors. The first factor was the dose of inorganic fertilizer, consisting of NPK (15-10-12) and urea fertilizer, with three levels as follows: no fertilizer (K0), 50% recommendation (K1), and 100% recommendation (350 kg ha^{-1} NPK + 250 kg ha^{-1} Urea) (Indonesia, 2022) (K2). The second factor was the concentration of the biosurfactant solution with four levels: 0 (B0), 0.1% (B1), 0.2% (B2), and 0.3% (B3). There were 3 × 4 = 12 treatment combinations, each replicated three times, resulting in 36 experimental units. Data from the experiments were statistically analysed using an F-test at a 5% significance level. If the treatment showed a significant effect, it was followed by an LSD test at the 5% significance level.

The main material for biosurfactant production was ripe lerak fruit, which was finely chopped and then macerated in 96% alcohol at a ratio of 1:5 (v/v) for two weeks, with daily shaking. The maceration process was conducted in dark-coloured glass bottles or stored in a dark place. After maceration, the lerak extract was filtered, and the filtrate was collected using a dropper or pasteur pipette according to the treatment dosage and added to the liquid organic fertilizer. Jamilah et al. (2020) explained that the liquid organic fertilizer was formulated through alternating semi-aerobic and anaerobic fermentation of the shrub species *Chromolaena odorata*, coconut husk, banana stem, cattle manure, and cow urine, with a volumetric ratio of 1:1:1:0.5:0.01 (v/v/v/v/v). The production process of the liquid organic fertilizer took four months, consisting of one month under semi-aerobic conditions and the following three months under anaerobic conditions, during which all solid materials were submerged in water at a 1:1 volume ratio.

The land to be used was measured and cleared of weeds and plant residues manually using a machete and hoe. The soil was tilled to a depth of 30 cm until loosened, ensuring no clumps remained. After soil preparation, 36 plots were created, each measuring 400 cm × 300 cm, with a planting distance of 50 × 40 cm, accommodating 40 plants per plot, and a spacing of 30 cm between plots. Soil observation involved taking random soil samples from a depth of 15 cm before soil preparation.

The application of LOF enriched with biosurfactants, according to the treatment, was sprayed as a mist over the entire maize crop using a hand sprayer with a 0.25-inch nozzle. Liquid Organic Fertilizer at a concentration of 50 mL L^{-1} water was applied every two weeks, starting from two weeks after planting until the plants formed ears and the leaves remained green.

Harvesting of maize was carried out when the plants were 90–110 days after planting (DAP), with the criteria being solid (full) and shiny kernels. Harvesting was performed by breaking off the maize stalks. Harvest parameters included the weight of ears per plot at harvest and the weight of dry kernels per hectare. The weight of dry kernels was determined by drying them to a moisture content of 14% and then weighing them using an analytical balance.

Soil analysis was conducted by determining soil pH at 45, 60, and 95 DAP. The pH was measured using a pH electrode with a soil-to-solvent ratio of 1:2.5. Agronomic parameters were measured before the flowering primordia stage, including plant height and Leaf Area Index (LAI), calculated by first determining the total leaf area using Equation 1 as described by L. Sun et al. (2021).

$$LAI = \frac{TLA}{PS} \quad [1]$$

Where TLA = k x (L x W) (Mondo et al., 2009); k= The constant value (k); L= The length of the i-th leaf; W= The width of the i-th maize leaf; Total Leaf Area (TLA)= Sum of all leaf areas per plant (m^2); PS (Plant Spacing) = Land area occupied by one plant (m^2); net assimilation rate (NAR) and relative growth rate (RGR).

Li et al. (2016) described the measurement of plant weight per unit leaf area over a specific period. Measurements were taken periodically during the vegetative phase of maize at 45, 60, and 95 DAP, using Equation 2.

$$\text{NAR} = \frac{W_2 - W_1}{T_2 - T_1} \times \frac{l_{nLD_2} - l_{nLD_1}}{LD_2 - LD_1} (g\ m^{-2} day^{-1}) \quad [2]$$

where W_1 = total dry weight at time T_1 (g); W_2= Total dry weight at time T_2 (g); T_1 and T_2 = First and second sampling times (days); LD_1 = Leaf area at time T_1 (m^2); LD_2 = Leaf area at time T_2 (m^2).

The Relative Growth Rate (RGR) was calculated in Equation 3 (Lamont et al., 2023).

$$\text{RGR} = \frac{l_n W_2 - l_n W_1}{T_2 - T_1} (mg\ g^{-1} day^{1}) \quad [3]$$

where W2 = Dry weight at time T2 (mg or g); W1 = Dry weight at time T1 (mg or g); T2 - T1 = Time interval (days).

Multiple linear regression models were used to predict maize crop yield (Y) based on several independent variables (X), such as pH, LAI, RGR, NAR, and shoot-root ratio, in order to understand the relationship between these variables and maize crop yield.

3. RESULTS

3.1. pH and plant height

Soil pH analysis before treatment and prior to dolomite ($CaMg(CO_3)_2$) application showed a pH of only 4.22. The application of 100 kg ha^{-1} dolomite resulted in an increase in soil pH to 6.10 at 45 days after planting (DAP). As maize plants matured from 45 to 60 and up to 95 DAP, a slight decrease in soil pH was observed. At 45 DAP, soil pH was higher with the application of 100% of the recommended synthetic fertilizer rate compared to lower fertilizer doses (Table 1).

The application of synthetic fertilizers significantly increased the height of the maize crop at 45 DAP, with the optimal dose being 50% applied, or 175 kg ha^{-1} NPK + 125 kg ha^{-1} Urea. The addition of biosurfactant to the liquid fertilizer did not show a significant difference. There was no interaction between the application of NPK and liquid organic fertilizer (LOF) on the growth of maize crops at 45 DAP. Nutrient availability was adequately met with the 50% recommended dose of NPK, and increasing the dose to 100% did not result in significant differences (Table 2).

3.2. Net assimilation rate (NAR)

The net assimilation rate (NAR) was significantly influenced by the interaction between biosurfactant-enriched liquid fertilizers (LOF) and synthetic fertilizers. Enriching the liquid organic fertilizer with 0.1% or 0.3% biosurfactant, along with the application of 50% synthetic NPK fertilizer, showed no significant difference compared to the application of 100% synthetic fertilizer. Therefore, LOF enriched with biosurfactants can reduce the need for synthetic NPK fertilizers while optimizing the NAR of maize crops from 45 to 60 DAP (Table 3).

Table 1. Soil pH development based on the growth stages of maize crops from 45, 60, and 95 days after planting (DAP) with the application of synthetic fertilizers

Chemical fertiliser substitution	Without liming	Days after planting given 100 kg ha^{-1} $Ca(CO_3)_2$		
	0	45	60	95
0% applied	-	5.94^{B}	5.84^{A}	5.25^{A}
50% applied	-	6.15^{AB}	5.82^{A}	5.02^{A}
100% applied	-	6.22^{A}	5.95^{A}	5.32^{A}
Average	4.22*	6.10**	5.87**	5.20**
CV (%)	-	6.27	5.86	6.93

Notes: Numbers followed by the same uppercase superscript letters in a column are not significantly different according to LSD (P<0.05); *) Very Acidic; **) Moderately Acidic (Tripathi et al., 2018)

Table 2. Plant height influenced by NPK and LOF enriched with biosurfactant at 45 DAP

Chemical fertiliser substitution	Biosurfactant-enriched liquid fertilisers				Average
	0%	0.1%	0.2%	0.3%	
	------------------------------------- cm ---				
0% applied	174.17	178.03	204.07	204.33	190.15^{B}
50% applied	194.70	213.17	205.37	212.20	206.36^{AB}
100% applied	204.33	212.20	220.87	220.87	214.57^{A}
Average	191.07a	201.13a	210.10a	213.57a	
CV (%)	8.12				

Notes: Numbers followed by the same capital letter in superscript in the same column are not significantly different according to LSD (p<0.05%)

Table 3. Net assimilation rate (NAR) of maize crops at 45 to 60 days after planting with NPK and biosurfactant-enriched liquid organic fertiliser (LOF)

Chemical fertiliser substitution	Biosurfactant-Enriched Liquid Fertilisers			
	0%	0.1%	0.2%	0.3%
	----------------------------- g m^{-2} --------------------------------------			
0% applied	6.0442^{cB}	6.3226^{bcC}	8.7081^{abB}	10.6622^{aB}
50% applied	10.5363^{bA}	14.0005^{aA}	11.5655^{bA}	14.9806^{aA}
100% applied	10.6622^{bA}	14.9806^{aA}	10.5622^{bA}	10.5622^{bB}
Average	9.0809^{aA}	11.7679^{aB}	10.2786^{aAB}	11.3817^{aB}
CV (%)	16.64			

Notes: Numbers followed by the same capital letter in superscript in the column and the same lowercase letter in the row are not significantly different according to LSD (p<0.05%)

Table 4. Development of leaf area index (LAI), RGR, and shoot-root ratio of maize crops at 45, 60, and 95 days after planting (DAP) with the application of NPK Phonska and biosurfactant-enriched liquid organic fertiliser (LOF)

Fertiliser treatments	Days after planting (DAP)						
	45	60	95	45-60	60-95	45	60
	LAI			RGR (mg day^{-1})		Shoot-root ratio	
Chemical fertiliser substitution							
0% applied	2.54^{B}	3.25^{B}	3.24^{B}	40.13^{B}	13.21^{A}	2.60^{B}	4.95^{A}
50% applied	2.89^{AB}	3.58^{A}	3.60^{A}	58.52^{A}	10.78^{A}	0.55^{A}	4.71^{A}
100% applied	2.96^{A}	3.52^{AB}	3.64^{A}	55.98^{AB}	11.62^{A}	0.52^{A}	5.24^{A}
Biosurfactant-Enriched Liquid Fertilisers							
0%	2.55a	3.20a	3.22^{b}	48.08a	14.33^{a}	1.81^{c}	5.11^{a}
0.1%	2.86a	3.51a	3.56^{ab}	53.45a	10.43^{c}	1.38^{b}	4.65^{a}
0.2%	2.84a	3.55a	3.59^{ab}	46.36a	1119^{bc}	1.16^{ab}	5.02^{a}
0.3%	2.80a	3.69a	3.70^{a}	59.70a	1392^{ab}	0.57^{a}	3.72^{a}
CV (%)	13.34	9.78	7.67	13.19	16.45	15.50	17.53

Notes: Numbers followed by the same uppercase and lowercase superscript letters in the same column are not significantly different at LSD (p<0.05)

3.3. Leaf area index (LAI), relative growth rate (RGR), and shoot-root ratio

The leaf area index (LAI) of maize crops at 45, 60, and 95 DAP is presented in Table 4. As the plant age increases, LAI also increases. The application of NPK fertilizer had a significant effect on LAI, while the application of Biosurfactant-Enriched Liquid Fertilizers did not significantly affect LAI, except at 95 DAP. The relative growth rate (RGR) of maize significantly differed between 45–60 DAP for plants receiving NPK but did not differ significantly between 60–95 DAP. The effect of biosurfactant-enriched liquid fertilizers on RGR was not significant between 45–60 DAP, but was significant between 60–95 DAP. Both NPK and Biosurfactant-Enriched Liquid Fertilizers had a significant effect on the shoot-root ratio at 45 DAP, but this effect was not significant at 60 DAP.

3.4. Dry maize cob yield

The highest yield of dry maize cobs reached 5.60 tons ha^{-1}, achieved with the application of 0.1% biosurfactant-enriched liquid fertilizers in combination with 50% applied NPK. Increasing the NPK dose to 100% resulted in a decrease in dry maize cob weight (Fig. 1 & Table 5). Therefore, on Ultisol soils where only 100 kg ha^{-1} of dolomite lime is applied, there is no need to increase the NPK fertilizer application to 100%, as the fertilizer will not be used optimally.

Description: K0 = 0% fertiliser; K1 = 50% recommendation of inorganic fertiliser; K2 = 100% recommendation of inorganic fertiliser; B0 = 0% concentration of the biosurfactant solution; B1 = 0.1% concentration of the biosurfactant solution; B2 = 0.2% concentration of the biosurfactant solution

Figure 1. The appearance of dry maize cobs ready for shelling according to the treatments

Table 5. Effect of NPK and biosurfactant-enriched liquid fertilisers on dry maize cob weight

Chemical fertiliser substitution	Biosurfactant-enriched liquid fertilisers			
	0%	0.1%	0.2%	0.3%
	---------------------------- kg plot^{-1}--------------------------------			
0% applied	2.92^{bC}	3.15^{abB}	3.20^{abB}	3.58^{aB}
50% applied	4.16^{bB}	5.60^{aA}	5.22^{aA}	5.47^{aA}
100% applied	5.48^{aA}	4.53^{aAB}	5.01^{aAB}	4.96^{aA}
CV (%)	12.26			

Notes: Numbers followed by the same capital letter in superscript in the column and the same lowercase letter in the row are not significantly different according to LSD (p<0.05%).

Table 6. The Pearson correlation test of pH, LAI, RGR, NAR, shoot-root ratio at 45 days after planting (DAP) to the yield of dry corn kernels.

	pH	LAI	RGR	NAR	Yield	Shoot- root ratio
pH	1					
LAI	0.515**	1				
RGR	0.341*	0.631**	1			
NAR	0.367*	0.378*	0.781**	1		
Yield	0.463**	0.466**	0.497**	0.512**	1	
Shoot- root ratio	-0.388*	-0.497**	-0.642**	-0.694**	-0.783**	1

Notes: **. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).

3.5. The correlations between the predictor variables (pH, LAI, RGR, NAR, and shoot-root ratio) and yield

The data show the results of Pearson correlation analysis between various variables (pH, LAI, RGR, NAR, Yield, and shoot-root ratio) and the variable yield. For LAI (leaf area index), there was a significant positive correlation with yield at the 0.01 significance level, with a moderate correlation strength. For RGR (relative growth rate), a significant positive correlation with yield was also observed at the 0.01 level, again with a moderate strength. Similarly, NAR (net assimilation rate) was significantly and positively correlated with yield at the 0.01 level, with a moderate strength. However, for the shoot-root ratio, there was a highly significant negative correlation with yield at the 0.01 level, with a strong correlation strength (Table 6).

The R value (0.805) is the multiple correlation coefficient between the predictors and the dependent variable. The R^2 value (0.647) is the coefficient of determination, indicating the proportion of variability in the dependent variable (yield) that can be explained by the predictor variables in the model. In this case, 64.7% of the variability in Yield can be explained by the variables pH, LAI, NAR, RGR, and shoot-root ratio (Table 7).

Table 7. The correlation relationships between pH, LAI, RGR, NAR at 45 Days After Planting (DAP) and the yield of dry corn kernels

Model	r	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.805[a]	0.647	0.588	0.73542

Notes: Predictors: (constant), shoot-root ratio, pH, LAI, NAR, RGR

Table 8. The analysis of variance (ANOVA) for the relationship of all predictor variables (pH, LAI, RGR, NAR and shoot-root ratio) with Yield.

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	29.775	5	5.955	11.010	.000[a]
	Residual	16.225	30	.541		
	Total	46.000	35			

Notes: Predictors: (constant), shoot-root ratio, pH, LAI, NAR, RGR; dependent variable: yield

The ANOVA results show that the multiple linear regression model involving the predictor variables pH, LAI, NAR, RGR, and shoot-root ratio significantly explains the variability in yield. The high F-value (11.010) and the very small p-value (0.000) indicate that this model is statistically significant, and the variability explained by this model is much greater than the variability not explained by the model (Table 8).

Table 9 shows that this regression equation provides a way to predict yield based on the values of pH, LAI, RGR, NAR, and shoot-root ratio. The coefficients for each variable indicate the expected change in yield for every one-unit change in that variable, assuming the other variables remain constant. The correlation coefficient (r = 0.805) indicates that this model has a strong ability to explain the variability in yield based on the included predictor variables.

Multiple linear regression analysis, showing the relationship between Yield and the variables (pH, LAI, RGR, NAR, and shoot-root ratio), with a correlation coefficient of 0.805, results in Equation 4.

$$\text{Yield} = 2.218 + 0.447(\text{pH}) + 0.05(\text{LAI}) + 0.0001(\text{RGR}) - 0.038(\text{NAR}) - 0.611\ \text{SR ratio} \quad [4]$$

with a correlation coefficient r = 0.805. Where yield = yield of maize; pH = Soil pH; LAI = Leaf area index; RGR = Relative plant growth; NAR = Net assimilation ratio; and SR ratio = Shoot-root ratio.

4. DISCUSSION

The present study demonstrated the dynamic response of soil pH and maize growth to the application of chemical fertilizers and Biosurfactant-Enriched Liquid Organic Fertilizers (LOF) on Ultisol soils. At the early growth stage (45 DAP) (Table 1), soil pH values were generally higher compared to later stages (60 and 95 DAP), mainly due to the initial application of lime (100 kg ha^{-1} $CaMg(CO_3)_2$) as a base treatment. Although this lime dose was lower than the general recommendation for Ultisols (2–4 tons ha^{-1}), it temporarily elevated the soil pH. Over time, soil acidification occurred as a result of plant nutrient uptake, root exudation of organic acids, and microbial activity, all of which contributed to lowering the pH in the rhizosphere. The application of NPK fertilizers further accelerated this decline through nitrification processes that release H^+ ions into the soil, supporting findings by Bravin (2018) and Bilyera et al. (2021). The observed pH values during maize growth were slightly below the critical threshold reported for optimal maize productivity (Baquy et al., 2018; Tupaki et al., 2017), indicating a potential limitation in nutrient availability under more acidic conditions.

In terms of plant growth performance (Table 2), the height of maize plants in this study was below the potential maximum for the P32 variety (248 cm), as reported by Ijaz et al. (2023), but higher than previously recorded heights on Ultisols by (Jamilah et al., 2024). This suggests that although chemical and biosurfactant-enriched fertilizers provided sufficient nutrients to sustain growth, other soil limitations, such as pH and inherent Ultisol fertility, constrained the full expression of maize's genetic potential.

Leaf area index (LAI) (Table 4), a key determinant of light interception and photosynthetic capacity, reached optimal values at 60 DAP, particularly in treatments where 50% NPK was combined with LOF. This demonstrates the potential of biosurfactant-enriched LOF to partly substitute chemical fertilizers without reducing the canopy development necessary for yield formation. Such results align with previous studies (Berdjour et al., 2020; Yuan-xue et al., 2013), emphasising that balanced nutrient supply enhances LAI and, subsequently, dry matter accumulation and grain production.

Relative growth rate (RGR) and net assimilation rate (NAR) showed trends consistent with plant development stages and nutrient management (Tables 3 and 4). Though RGR declined as the plant matured, high LAI ensured adequate photosynthesis and biomass accumulation. However, the regression analysis revealed that among all growth parameters, the shoot-to-root ratio had the most significant (negative) impact on yield, indicating that excessive shoot allocation may reduce root system effectiveness in nutrient and water uptake—essential functions in Ultisol environments where subsoil acidity and aluminium toxicity prevail. Lower shoot-root ratios associated with both LOF and partial chemical fertilizer substitution suggest improved root development, enhancing nutrient foraging and overall plant resilience. This result supports the hypothesis that optimal below-ground biomass allocation is critical for maximising yield on nutrient-stressed soils (Guo & York, 2019a, 2019b; X. Sun et al., 2021).

Furthermore, the positive impact of biosurfactant-enriched LOF was evident in biomass and yield formation. The best dry cob weight and maize yield (5.60 tons ha^{-1}) (Fig. 1 & Table 5) were achieved with 50% NPK combined with 0.1% biosurfactant-enriched LOF, surpassing full NPK treatment, thus indicating the potential of this integrated fertilisation strategy to reduce chemical inputs without sacrificing yield. Regression and correlation analyses confirmed the shoot-root ratio as the main predictor of yield variability, underscoring the importance of nutrient-induced root growth stimulation for productivity improvement.

Table 9. Multiple linear regression analysis of all predictor variables (pH, LAI, RGR, NAR, and shoot-root ratio) to yield

Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.218	1.699		1.305	0.202
	pH	0.447	0.315	0.189	1.421	0.166
	LAI	0.050	0.359	0.023	0.140	0.889
	RGR	0.0001	0.015	0.006	0.029	0.977
	NAR	-0.038	0.079	-0.101	-0.486	0.631
	srratio	-0.611	0.129	-0.763	-4.734	0.000

Notes: Dependent variable: yield

Pearson correlation analysis showed the relationship between each variable and Yield, with the shoot-root ratio indicating a strong negative relationship (Table 6). The regression model has a high multiple correlation coefficient (Table 7), indicating that the model can explain the variability in Yield effectively. ANOVA shows that the regression model is statistically significant (Table 8), confirming that the model is valid in explaining Yield variability. The regression coefficients reveal the impact of each variable on Yield, with only the shoot-root ratio having a significant effect, while other variables were not significant. Overall, the multiple linear regression model involving the analyzed variables provides a clear picture of how these variables affect yield, with the shoot-root ratio being the main significant predictor. If the shoot-root ratio is high, it will decrease maize yield due to its significantly negative relationship. Therefore, it is important to determine the appropriate fertilizer treatment dosage to reduce the shoot-root ratio in order to increase maize yield.

The equation provided—yield = 2.218 + 0.447(pH) + 0.05(LAI) − 0.0001(RGR) − 0.038(NAR) − 0.611(Shoot-root ratio) (Table 9)—represents a model for predicting yield in agricultural settings. This equation incorporates various factors such as pH, leaf area index (LAI), relative growth rate (RGR), net assimilation rate (NAR), and shoot-root (SR) ratio to estimate crop yield. The correlation coefficient (r = 0.805) indicates a strong positive relationship between the predicted yield and the input variables, suggesting that these factors significantly influence crop productivity. Pacentchuk et al. (2020) explained that factors like pH levels, plant growth rates, and shoot-root ratios play crucial roles in determining the final yield of crops, highlighting the importance of soil quality, plant development, and resource allocation in agricultural production.

Similarly, Rinehart et al. (2024) demonstrated that the higher the shoot-root ratio in maize, the lower the yield can be due to various factors identified in their research. A study on maize hybrids over an 80-year period found that modern hybrids with decreased root biomass and length, leading to a lower root-to-shoot ratio, had been selected for higher yields, indirectly reducing root system size. Additionally, Shao et al. (2018) demonstrated that maize root system architecture in response to planting densities revealed that high-density planting reduces the root-to-shoot ratio, total root length per plant, and root biomass per plant, negatively impacting grain yield per plant and nutrient accumulation per hectare. Furthermore, a study on pea genotypes showed that a higher shoot-root ratio significantly influences the number and weight of seeds planted, indicating that an imbalanced allocation of photosynthates towards shoots can negatively impact yield. These findings collectively suggest that a higher shoot-root ratio can lead to lower yields in maize due to compromised root development and resource allocation.

Overall, this study illustrates the complex but manageable interactions between soil chemistry, plant physiology, and fertilizer management on Ultisols. Integrating biosurfactant-enriched LOF not only reduced dependence on chemical fertilizers by up to 50% but also maintained soil pH closer to optimal levels, promoted balanced biomass partitioning, and supported sustainable maize production. These findings advocate for broader adoption of such bio-based amendments in acid soil farming systems to enhance crop performance while mitigating environmental and economic costs associated with intensive fertilizer use.

5. CONCLUSION

Over time, the soil pH of maize crops tends to decrease but remains within the slightly acidic range. Increasing the dosage of NPK fertilizer generally raises soil pH, with a significant impact observed at 45 days after planting (DAP). In contrast, biosurfactant-enriched liquid fertilizers show a more noticeable effect on variables such as leaf area index (LAI), relative growth rate (RGR), and shoot-to-root ratio (SRR) at 60 DAP compared to 45 DAP. The highest maize cob yield of 5.60 kg $plot^{-1}$ (6.6 tons per hectare) was achieved by applying 50% of the recommended NPK rate combined with 50 mL L^{-1} of 0.1% Biosurfactant-enriched liquid fertilizers. Managing the shoot-root ratio through appropriate fertilizer treatments and planting strategies is crucial for optimizing maize yield. Addressing root development and balancing resource allocation can significantly enhance crop productivity and efficiency.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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