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Responses of Soil Nutrient Status, Mycorrhizal Development, and Sweet Corn Productivity to Indigenous Mycorrhizal Bioameliorant in Sandy Soil

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ABSTRACT

Sandy soils retain nutrients poorly, and crops grown on them are commonly nitrogen- and phosphorus-limited. Direct comparisons of indigenous arbuscular mycorrhizal fungi (IAMF), cattle manure (CM), and their combination in such soils are scarce. At Muncuk Karya, Mataram, West Nusa Tenggara, Indonesia, five bioameliorant treatments were randomised in three blocks (15 plots): untreated control (B0); 10 t ha^{-1} CM (B1); 3 t ha^{-1} IAMF inoculum (B2); 5 t ha^{-1} CM + 1.5 t ha^{-1} IAMF (B3); and 10 t ha^{-1} CM + 3 t ha^{-1} IAMF (B4). Measurements included soil total N and available P, plant N and P uptake, AMF spore density, root colonisation, vegetative growth, biomass, and yield. Formulations were characterised by scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX). B2 gave the broadest response, increasing soil total N by 60.2%, available P by 425.3%, spore density by 93.1%, and root colonisation by 15.6% over B0. It also recorded the highest fresh ear weight, dry ear weight, and fresh ear yield (+159.4%, +229.8%, and +63.1%). Corrected LSD placed B2's fresh ear yield (6.90 kg plot^{-1}) on a par with B1 (6.10 kg plot^{-1}), but well above B0, B3, and B4. Adding CM to IAMF provided no gain, although the non-factorial design leaves additivity and interaction untestable. SEM-EDX distinguished the formulations by elemental composition, but these differences were unrelated to soil and plant results. IAMF without manure was preferable;

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because the inoculum carried a substrate and no carrier-only control was included, the effect should be attributed to the complete formulation, not the fungi alone.

Keywords: Arbuscular mycorrhizal fungi, bioamelioration, nutrient uptake, sandy soil, sweet corn

INTRODUCTION

Sandy soils carry a substantial share of tropical and semiarid agriculture, yet what can be grown on them is bounded by the same handful of limitations: little organic matter, an exchange complex with almost no holding capacity, rapid drainage, and the nutrient losses that follow from it. Crops that demand a great deal of nitrogen and phosphorus run into those limits soonest, and sweet corn (*Zea mays* L. var. *saccharata*) is one of them. The field used for this experiment was typical in that respect, with 69% sand, 29% silt, and only 2% clay, a texture on which applied fertiliser has little to bind to and on which fertility management becomes the governing problem. Where mineral inputs are unlikely to stay in the root zone long enough to be useful, there is a case for testing biological amendments instead, on the grounds that they may improve nutrient capture by the crop and strengthen the working relationship between soil organisms and roots (Zenebe et al., 2024).

Arbuscular mycorrhizal fungi (AMF) colonise roots and send hyphae into soil lying beyond the depletion zone the root has already created. Phosphorus benefits disproportionately from that extra reach, since it moves so little. In maize, AMF symbiosis has repeatedly been associated with better P acquisition and with changes in the rhizosphere processes that mobilise nutrients (Fall et al., 2023; Lu et al., 2023; Xu et al., 2024)and nitrogen dynamics within the soil-plant system respond to the symbiosis as well (Qiu et al., 2022). Agronomically, none of this counts for anything unless the association is established in the first place, which is why two things were tracked here: spore density, a count of the propagules held in the soil, and root colonisation, a measure of how far the association has spread through the root system. Where colonisation is extensive, the extraradical network tends to be denser, and it is that network which gains access to nutrients the root itself will never reach.

Indigenous AMF, as the term is used here, refers to an inoculum built from fungal populations occurring naturally in the sandy dryland soil of Akar-Akar Village, North Lombok, Indonesia. It is a statement of regional origin within Lombok and nothing more; the fungi were not collected at the Mataram field site. How well any biological amendment performs will depend on what it is introduced into, from the cropping history to the condition of the soil and the particular pairing of plant and microbe, and for indigenous inocula in particular, adaptation to local soils and compatibility with the host have been argued to be preconditions for effectiveness (Higo et al., 2018; Verbruggen & Kiers, 2010). We have examined related questions before. Indigenous AMF inoculation improved

nutrient uptake and maize productivity in sandy soil (Astiko et al., 2013b), and P uptake, growth, and yield in soybean (Astiko et al., 2013a). That soybean work was a pot study set against several nutrient sources, and there it was the AMF-cattle manure combination that performed best; the sweet corn field experiment reported here points the opposite way, with 3 t ha^{-1} IAMF alone ahead of the manure-IAMF mixtures. Neither of those earlier papers went beyond crop nutrient acquisition and productivity, whereas soil N and P status, mycorrhizal development, plant N and P uptake, biomass accumulation, and yield are followed together in the present study. MAA01, the inoculum applied, originates from dryland soil at Akar-Akar Village, North Lombok, West Nusa Tenggara, and has previously been shown to establish mycorrhizal associations and to support nutrient acquisition and crop performance (Astiko et al., 2015, 2019). Those two things, a regional origin and a documented record under sandy, dryland conditions, are what recommended it.

No inoculum performs identically everywhere. Outcomes shift according to which fungus is involved, which host it meets, the state of the soil, and how much nutrient is already on hand. Sweet corn, for instance, differs in nutrient uptake and biomass depending on the AMF species applied (Carrara & Heller, 2022), and across a maize crop, irrigation and fertilisation regimes have been shown to alter colonisation, spore numbers, hyphal development, and community composition alike (Lü et al., 2020). Indigenous AMF may account for a large fraction of maize P acquisition, though that fraction contracts as soil P climbs (Qin et al., 2022). Set cattle manure beside indigenous AMF and the mycorrhizal response can go three ways, enhanced, unchanged, or suppressed, depending on nutrient supply and on whether what the plant gains outweighs the carbon it must spend on the fungus. An inoculum, in short, is only worth judging in the soil, crop, and nutrient-management setting where it will actually be used.

Cattle manure changes the soil it enters, adding nutrients and organic matter, and in doing so it can change how much the plant needs its fungal partner. A rise in available P in particular may help the crop while reducing its reliance on the mycorrhizal route. That is the reasoning behind comparing indigenous AMF inoculum on its own against manure on its own and against the two applied together. We made no prior assumption of synergy or additivity. The comparison was set up so that soil nutrient status, mycorrhizal development, nutrient uptake, biomass, and crop productivity could report what the formulations actually did.

We use mycorrhizal bioameliorant to mean an indigenous AMF-based formulation applied to sandy soil in order to alter a defined set of soil and crop characteristics. Its effectiveness here was judged on soil total N, available P, AMF spore density, root colonisation, plant nutrient acquisition, biomass, and yield, and on nothing else. The word carries no claim that the amendment improves soil quality across the board, physically, chemically, and biologically; our interpretations stay inside the list of variables we measured.

That AMF contribute to crop nutrition and productivity is no longer in dispute, but their behavior on sandy soils has been examined unevenly. P uptake and maize yield have been covered (Hou et al., 2021), as have nutrient accumulation and root exudation (Ma et al., 2022), rhizosphere microbial processes (Zhou et al., 2022), N and P acquisition in sweet corn (Wu et al., 2023), and crop responses to AMF applied alongside fertiliser (Subaedah et al., 2023). What remains unresolved is how indigenous AMF inoculation performs, by itself or with cattle manure, when soil fertility, mycorrhizal development, and crop performance are weighed together on a sandy soil. Whether more amendment reliably buys better soil and a better crop can only be answered by setting IAMF-only, manure-only, and combined strategies side by side.

We therefore asked how indigenous AMF inoculation, cattle manure, and selected combinations of the two affect soil fertility, mycorrhizal development, plant N and P acquisition, biomass production, and sweet corn yield in sandy soil. Our expectation was that the five treatments would separate on soil total N and available P, spore density, root colonisation, nutrient uptake, biomass, and yield; that the IAMF-only treatment would differ from the others across those variables; and that it would at least improve on the untreated control under the conditions of this trial.

MATERIALS AND METHODS

Experiment Site and Materials

The trial ran from May to July 2026 at Muncuk Karya, Pejeruk Karya Village, Ampenan District, Mataram City, West Nusa Tenggara, Indonesia (8°26′27.6″ S, 116°06′07.2″ E), about 5 m above sea level. Samples were analysed afterwards at the Microbiology and Soil Chemistry Laboratories, Faculty of Agriculture, University of Mataram. Materials comprised Bonanza F1 sweet corn (*Zea mays* L.), the indigenous arbuscular mycorrhizal fungi (IAMF) isolate MAA01, cattle manure (CM), urea, NPK Phonska, Green Tonik, and OrgaNeem; Table 1 lists the reported composition and active constituents of the last two. Field operations and laboratory work used standard equipment for crop management, soil and plant sampling, sample preparation, nutrient determination, and mycorrhizal assessment. Roots destined for colonisation counts were cleared in 10% KOH and stained with methylene blue, with filter paper and distilled water used during preparation. Spore density was obtained by sieving followed by microscopic counting.

Treatments were laid out as a single-factor randomised complete block design (RCBD), five bioameliorant treatments by three replications, giving 15 experimental units: B0, neither CM nor IAMF; B1, 10 t ha^{-1} mature CM; B2, 3 t ha^{-1} IAMF inoculum; B3, 5 t ha^{-1} mature CM with 1.5 t ha^{-1} IAMF inoculum; and B4, 10 t ha^{-1} mature CM with 3 t ha^{-1} IAMF inoculum (Table 2).

Table 1
Reported composition and active constituents of the Green Tonik and OrgaNeem

Parameter	Green Tonik	OrgaNeem
Product category	Liquid supplementary fertiliser	Botanical pesticide
Main source	Commercial nutrient formulation	Neem seed extract (Azadirachta indica)
Nitrogen (N)	14.73%	Not reported
Phosphorus (P_2O_5)	1.56%	Not reported
Potassium (K_2O)	2.55%	Not reported
Sulfur (S)	0.33%	Not reported
Calcium (Ca)	1.33%	Not reported
Magnesium (Mg)	0.02-0.22%*	Not reported
Iron (Fe)	706.38 ppm	Not reported
Copper (Cu)	2.25 ppm*	Not reported
Zinc (Zn)	111.77 ppm	Not reported
Manganese (Mn)	17.18 ppm	Not reported
Boron (B)	Reported	Not reported
Molybdenum (Mo)	8.44 ppm*	Not reported
Azadirachtin	Not reported	0.8-1.4%
Protein	70.32%*	Not reported
Lipid	1.18%*	Not reported
Other Organic Compounds	1.55%*	Neem-derived bioactive compounds

Source: PT Angkasa Raya Berjaya (n. d.); Badan Penelitian dan Pengembangan Pertanian (2006)

Table 2
Cattle manure and indigenous arbuscular mycorrhizal fungi (IAMF) treatments and application rates used in the field experiment

Treatment	Cattle Manure (t ha^{-1})	IAMF Inoculum (t ha^{-1}) *
B0	0	0
B1	10	0
B2	0	3.0
B3	5	1.5
B4	10	3.0

Note. *A formulation based on the Glomus mosseae isolate MAA-01 yields 2,500 spores per 20 g of powder, with a root colonisation rate of 95% (Astiko et al., 2019)

The site carried a sandy loam of 69% sand, 29% silt, and 2% clay. Composite sampling preceded treatment: cores were taken from the 0-20 cm layer at 20 points distributed across the field and combined into a single sample, from which initial physical, chemical, and mycorrhizal properties were determined. Minimum tillage was used in land preparation, weeds were cleared, and the field was then divided into 15 plots according to the RCBD

set out above, three to each treatment. Plot size was 3 m × 2 m (6 m²), with 30 sweet corn plants per plot.

Dryland soil at Akar-Akar Village, North Lombok, was the source of the IAMF material used here. MAA01 forms part of an indigenous AMF collection assembled earlier from sandy dryland sites in that district, where its contribution to crop nutrient acquisition and productivity had already been examined (Astiko et al., 2015, 2019). In physical terms the formulation is a growth substrate carrying spores, hyphae, and colonised root fragments. Counts reported previously place MAA01 at approximately 2,500 spores per 20 g of substrate, equivalent to some 125 spores g^{-1}. The isolate is maintained as indigenous material, and no attempt at species-level molecular identification was made in this study. An infectivity assay served to confirm viable propagule density; trap-host root colonisation, however, was not determined separately for the batch that went into the field.

Inoculum Preparation, Measurements, and Data Analysis

IAMF were obtained from North Lombok following the collection procedure of Astiko et al. (2019). The resulting inoculum held soil substrate, colonised root fragments, hyphae, and spores produced by pot-culture multiplication. Multiplication of this kind relies on a compatible host, because AMF need living roots in order to colonise and to form new propagules (Paré et al., 2022; Tanaka et al., 2022). We filled polybags with about 5 kg of growth medium, soil mixed with sterilised cattle manure, inoculated each with IAMF propagules, and grew maize in them for roughly 50 days. The maize was then harvested and the substrate with its colonised roots air-dried for seven days. Dried substrate passed through a 2-mm sieve; the colonised roots were ground fine. The two fractions were recombined and mixed until uniform.

MAA01 is a carrier-based product: substrate, spores, hyphae, and root fragments together. Since soil and sterilised cattle manure made up the propagation substrate, applying the inoculum also delivered a small quantity of nutrients and organic matter alongside the viable propagules. No carrier-only or inactivated-inoculum treatment was included in the design. Responses to MAA01 therefore cannot be assigned to AMF biology alone.

CM and IAMF inoculum went on at planting at the rates set for each treatment and were worked into the planting area to about 10 cm depth. Bonanza F1 sweet corn was sown two seeds per hole at 60 × 40 cm. Gaps and weak seedlings were replanted at 1 week after planting (WAP), and plots were thinned to one plant per hole at 2 WAP. Every plot, whatever its treatment, received mineral fertiliser at half the local recommendation, 175 kg ha^{-1} urea and 125 kg ha^{-1} NPK Phonska, split equally between 1 and 2 WAP. Weeds were pulled by hand, and plots were irrigated whenever rainfall fell short of crop demand.

Height and leaf number were recorded at 4, 6, and 8 WAP, while soil nutrient status, plant N and P uptake, and rhizosphere sampling were all handled at 6 WAP. For destructive

sampling, three plants per treatment per block were taken from an area reserved outside the main plot, so that their removal would leave later observations undisturbed. These three plants functioned as subsamples and not as independent replicates: a single mean value per treatment per block was calculated from them, and it was that value which entered the analysis. Three block replicates within the RCBD therefore underpin the statistics, and pseudoreplication is avoided.

Plant material from the harvest was oven-dried at 60 °C until constant mass was reached, then weighed. The dried samples were ground to a fine powder and homogenised ahead of digestion. Tissue N was determined by the Kjeldahl method and P colorimetrically following acid digestion. Per-plant nutrient accumulation was derived afterwards from the tissue concentration and its corresponding dry biomass.

At 6.75, the initial soil pH was close to neutral; on that basis, available P was extracted with sodium bicarbonate ($NaHCO_3$) according to the Olsen method.

Tissue concentration and whole-plant accumulation were kept as separate variables. Accumulation was obtained by combining the measured N or P concentration with the dry biomass of the plant. For concentrations expressed as a percentage (%), nutrient uptake (mg plant^{-1}) = dry biomass (g plant^{-1}) × nutrient concentration (%) × 10. For concentrations in g kg^{-1}, nutrient uptake (mg plant^{-1}) = dry biomass (g plant^{-1}) × tissue nutrient concentration (g kg^{-1}). Results are reported as mg plant^{-1}.

At 6 WAP, mycorrhizal development was assessed from spore density and root colonisation, three plants being sampled at random from each plot. Wet sieving and decanting (Brundrett et al., 1996) were used to recover spores from 100 g of rhizosphere soil, the suspension passing successively through 250, 106, 53, and 38 µm sieves. Whatever was retained on the 38 µm sieve went through centrifugation at 2000 rpm for 15 min, resuspension in 50% sucrose, and a second spin at 2000 rpm for 10 min. Counting was done at 40× under a stereomicroscope, with results expressed per 100 g soil. Colonisation was scored on root segments of roughly 1.5 cm, cleared in 10% KOH, acidified in 0.1 N HCl, stained with methylene blue, and read at 40× by the gridline-intersect method (Giovannetti & Mosse, 1980); the figure reported is the percentage of examined intersections carrying mycorrhizal structures. Throughout, the plot was taken as the experimental unit, and within each replicate the mean of the three plants was what entered the analysis.

Destructive sampling at 8 and 11 WAP supplied the root and shoot biomass data. Plants taken on either date were divided into root and shoot fractions, weighed fresh, dried in an oven to constant weight, and weighed a second time. For each plot, fresh and dry biomass were calculated separately at both sampling dates.

A subset of the bioameliorant formulations was characterised by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX), the first for surface character and the second for elemental composition. Specimens intended for imaging were

dried, mounted on metal stubs, and coated with roughly 10 nm of gold-palladium (Au-Pd) against charging, then examined on a JEOL JCM-700 (JEOL Ltd., Tokyo, Japan) at 15 kV and 1000× magnification at the Integrated Laboratory, Universitas Islam Negeri Mataram, Indonesia. Elemental analysis was run separately at the Integrated Laboratory, Universitas Sumatera Utara, Indonesia, on a JEOL JSM-6510LA fitted with EDX; those specimens were deliberately left uncoated, since the metal film would otherwise interfere. Spectra were taken from representative areas of each specimen and quantified as mass percentage (Mass%) and atomic percentage (Atom%) for carbon (C), nitrogen (N), oxygen (O), magnesium (Mg), phosphorus (P), potassium (K), calcium (Ca), and zinc (Zn). Because EDX reports only what lies within the small volume it samples, and measures neither nutrient release nor solubility nor biological availability, the resulting figures are treated throughout as a description of the materials (Kumaragamage et al., 2024).

Data were analysed by ANOVA for a randomised complete block design, treatment fixed and block random, with the plot as the experimental unit and the mean of three sampled plants per plot as the observation. Plant height and leaf number, measured repeatedly, were analysed with treatment, time, and treatment × time terms. Model assumptions were checked beforehand. Where the F-test was significant, means were separated by Fisher's protected least significant difference (LSD) at the 5% significance level ($P < 0.05$). Minitab 22.1.0 was used throughout.

RESULTS AND DISCUSSIONS

Effects of Bioameliorants on IAMF Spore Density and Root Colonisation

Treatment affected both spore density and root colonisation at 6 WAP (Figure 1). The largest spore population, 2,335.33 per 100 g soil, was recorded under B2, which received 3 t ha^{-1}

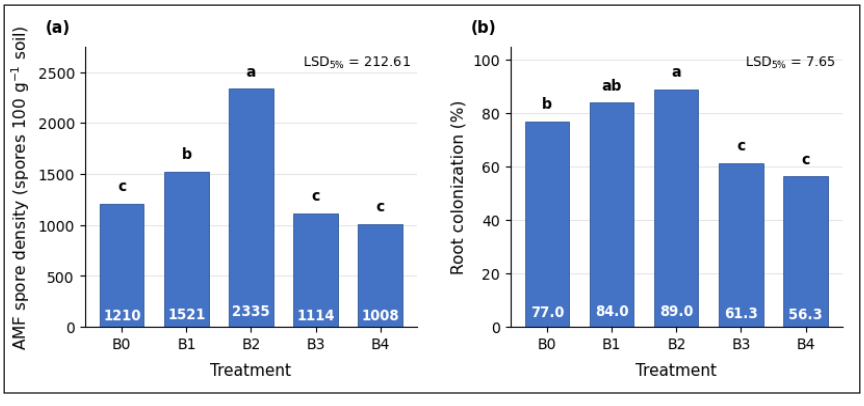


Figure 1. Effects of indigenous arbuscular mycorrhizal fungi and cattle manure treatments on (a) AMF spore density (spores per 100 g soil) and (b) root colonisation (%) at 6 weeks after planting (WAP). Different lowercase letters indicate significant differences among treatments according to the 5% LSD test at the significance level ($P < 0.05$)

IAMF inoculum and no cattle manure, and it stood significantly above every other treatment (Figure 1a), 93.1% higher than the untreated control. Colonisation followed suit, climbing from 77.0% under B0 to 89.0% under B2 (Figure 1b), an absolute gain of 12 percentage points and a relative one of roughly 15.6%. Since both measures rest on morphological identification, what they report is the state of the AMF population and colonisation in the soil as a whole, rather than the portion attributable to MAA01 as distinct from fungi already present. Cattle manure applied by itself (B1) likewise raised spore numbers and colonisation above the control. Weaker results came from the combined CM-IAMF treatments, with B4 last at 1,008.33 spores per 100 g soil and 56.3% colonisation.

That B2 outperformed the combined treatments on both mycorrhizal measures indicates that adding cattle manure did nothing for mycorrhizal development here. AMF establishment is known to track soil nutrient conditions, and a change in nutrient supply alters how much a plant depends on the symbiosis (Jiang et al., 2021; Ma et al., 2020). Shifts in extraradical hyphal growth, in transfer across the fungus-root interface, or in the plant's reliance on the mycorrhizal pathway could each be involved. We measured none of them, and they remain possibilities drawn from the literature rather than explanations these data can support. On the crop side, B2 accumulated more biomass than B3 and B4, which suggests that the larger amendment inputs in the combined treatments did not convert into growth. Because the treatment structure is non-factorial, the separate contributions of manure and IAMF, and any interaction between them, cannot be resolved statistically; the differences hold for the five specific formulations compared.

The ranking in Figure 1 carried through to the crop. B2, highest in both spore density and colonisation, also produced the most biomass and the largest yield, whereas B4 combined weak mycorrhizal development with soil N, available P, and plant N and P uptake above those of the untreated control. Effective IAMF bioamelioration in this sandy soil evidently rests on more than nutrient supply; the soil-AMF-plant relationship has to work as well. One limit should be kept in view: morphological assessment cannot separate the introduced MAA01 inoculum from the resident AMF community, so treatment effects describe overall mycorrhizal development rather than the behavior of MAA01 specifically.

Effects of Bioameliorants on Soil Nutrient Status and Plant N and P Uptake

Soil total N, available P, and plant N and P accumulation at 6 WAP all differed among treatments (Table 3), and B2 topped every one of them. Plant accumulation was derived from tissue concentration and dry biomass and is reported per plant (mg plant^{-1}). Under B2, soil total N reached 4.100 g kg^{-1}, available P 76.164 mg kg^{-1}, plant N uptake 0.194 mg plant^{-1}, and plant P uptake 3.164 mg plant^{-1}, each significantly above the remaining treatments at the 5% level. Relative to the untreated control, these are gains of 60.2% in soil total N, 425.3% in available P, 162.2% in plant N uptake, and 47.1% in plant P uptake.

Table 3
Effects of cattle manure and indigenous arbuscular mycorrhizal fungi (IAMF) treatments on soil total N, available P, and plant N and P uptake at 6 weeks after planting (WAP)

Treatment	Soil Nutrient		Nutrient Uptake	
	Total N (g kg-1)	Available P (mg kg-1)	N Uptake (mg plant-1)	P Uptake (mg plant-1)
B0: Control	2.560e	14.499e	0.074d	2.151c
B1: 10 t ha^{-1} CM	3.488b	18.838d	0.174b	2.778b
B2: 3 t ha-1 IAMF	4.100a	76.164a	0.194a	3.164a
B3: 5 t ha^{-1} CM + 1.5 t ha^{-1} IAMF	3.247c	57.238b	0.112c	2.494bc
B4: 10 t ha^{-1} CM + 3 t ha^{-1} IAMF	2.900d	47.477c	0.108c	2.272c
LSD 5%	0.120	3.055	0.007	0.380

Note. Means followed by the same letter are not significantly different according to the LSD test at the 5% significance level ($P < 0.05$). IAMF = indigenous arbuscular mycorrhizal fungi; CM = cattle manure

The MAA01 inoculum carried soil- and manure-derived material with it, so the improvement cannot be credited to AMF biology by itself.

What B2 delivered in soil N and available P came from the complete MAA01 formulation, viable propagules and carrier together. The response fits what AMF are known to do for nutrient acquisition, but carrier material also supplies nutrients and organic matter, and this design cannot tell the two apart. AMF have been shown to contribute to P acquisition by extending hyphae through soil the root does not reach, and to influence rhizosphere microbial processes involved in nutrient turnover (Keyes et al., 2022; Liang et al., 2022; Wang et al., 2023). Whether those pathways operated here was not tested.

The combined treatments produced no additive nutrient response. Soil total N fell to 3.247 g kg^{-1} under B3 and 2.900 g kg^{-1} under B4, and available P to 57.238 and 47.477 mg kg^{-1}. Plant N uptake dropped to 0.112 and 0.108 mg plant^{-1} and P uptake to 2.494 and 2.272 mg plant^{-1} in the same order. More amendment did not mean more available nutrient or more uptake. Context dependence of this kind matches evidence that P acquisition through indigenous AMF is governed by soil P availability, and that greater mycorrhizal P uptake does not scale into proportionally greater crop growth (Qin et al., 2022).

Across a long list of measurements, among them spore density, root colonisation, root and shoot biomass, dry matter production, and sweet corn yield, B2 came out in front, and the fact that these improvements moved in step suggests a favorable alignment between soil conditions, mycorrhizal development, and crop performance under that treatment. Indigenous AMF associated with maize roots have been reported to assist phosphorus acquisition and to support growth and productivity, the size of the benefit depending on fungal community and soil environment (Tatewaki et al., 2023). Our data, though, demonstrate co-occurrence and not a causal chain. Propagules and carrier were mixed in the inoculum; no carrier-only control was included, and neither nutrient transformations

nor microbial activity were monitored directly, so the mechanism underlying the response remains open.

Effects of Bioameliorants on Sweet Corn Vegetative Growth

Treatment affected plant height and leaf number, although which treatment led changed from one sampling date to the next (Figure 2). B1, B2, and B4 were taller than B0 and B3 at 4 WAP, and B2 and B4 carried the most leaves. Two weeks later, the tallest plants were those of B1, at roughly 58.33 cm, with B2 next at about 53.00 cm and B0 shortest; leaf number at 6 WAP was much the same across B1, B2, B3, and B4, all of them above B0.

By 8 WAP, height placed B1 and B2 together in the top statistical group, B3 in an intermediate position, and B0 and B4 behind. Leaf number was greatest under B2 at 11.33 per plant, against 9.00 in B0. Expressed relative to the control, final height and leaf number under B2 were higher by about 22.0% and 25.9%. Late vegetative performance under this treatment was therefore strong, and most obviously so in leaf production.

Conditions under B2 may simply have suited nutrient acquisition and mycorrhizal functioning in a soil that had little to offer. Positive associations between colonisation and nutrient accumulation, photosynthetic activity, and biomass development have been reported for maize (Gong et al., 2023; Lang et al., 2022) and the explanation usually offered is hyphal extension into soil beyond the root zone, which matters most for

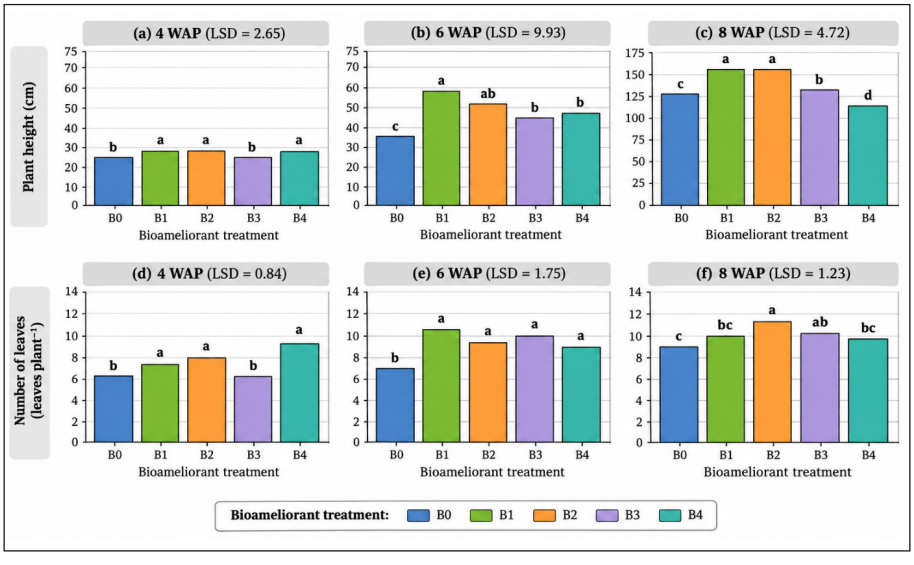


Figure 2. Effects of bioameliorant treatments on plant height at (a) 4, (b) 6, and (c) 8 weeks after planting (WAP), and on the number of leaves per plant at (d) 4, (e) 6, and (f) 8 WAP. Different lowercase letters above the bars indicate significant differences among treatments within the same observation time according to the least significant difference (LSD) test at the 5% significance level ($P < 0.05$). Statistical comparisons were performed separately for each observation time

phosphorus because phosphorus moves so little (Qiu et al., 2024). Hyphal extension was not measured in this experiment, nor was nutrient transfer through the fungal network, nor the physiology underlying either; these remain interpretations rather than mechanisms we have demonstrated.

Treatment rankings were not stable. They changed between 4, 6, and 8 WAP, which means performance was not constant through the crop cycle. Because colonisation was assessed on one date only, however, the growth trajectory cannot be taken as evidence that mycorrhizal function strengthened over time. Nutrient availability, root development, and the mycorrhizal association itself could each have contributed. In sweet corn grown in the field, AMF inoculation has improved vegetative growth, root and shoot biomass, nutrient uptake, and yield, most visibly under limiting P and water (El-Sawah et al., 2023), while nutrient supply has itself been shown to modify root development, colonisation, and hyphal proliferation (Zhang et al., 2023).

Neither combined treatment beat IAMF alone consistently. B4 produced plenty of leaves at 4 WAP and the shortest plants by 8 WAP, while B3 generally sat in the middle. With a non-factorial structure, these contrasts cannot be read as additive or interactive effects. They show that the tested formulations differed in vegetative response, and that B2 was among the strongest late in the season.

Effects of Bioameliorants on Root and Shoot Biomass

Fresh and dry biomass differed among treatments at both 8 and 11 WAP, and biomass rose between the two dates in every treatment (Figure 3). B2 produced the greatest fresh and dry shoot and root biomass at 11 WAP, alongside the high soil total N and available P, plant N and P uptake, spore density (2,335.33 spores per 100 g soil), and root colonisation (89%) already reported for it. B3 and B4 produced less biomass and showed lower colonisation (61.33-56.33%) and spore density (1,114.00-1,008.33 spores 100 g^{-1} soil). Greater amendment input did not correspond to greater mycorrhizal development or greater biomass.

Under B2, the proportional rise in dry biomass outstripped that in fresh biomass, which points to dry matter accumulation rather than to tissue water content. Where AMF have been linked to biomass gains in maize, improved root development and nutrient acquisition are the usual attribution, with the magnitude governed by nutrient supply, amendments, and environment. In one such case, maize receiving AMF together with mineral nutrients outproduced several richer amendment combinations in shoot and root dry biomass, an argument that piling on inputs maximises nothing (Zenebe et al., 2024), and a pattern that the advantage of B2 over B4 here matches. Nutrient inputs can also work the other way: N-P fertilisation in particular has been shown to depress native AMF colonisation and alter the maize growth response (Ujvári et al., 2023). Given the non-factorial design, the

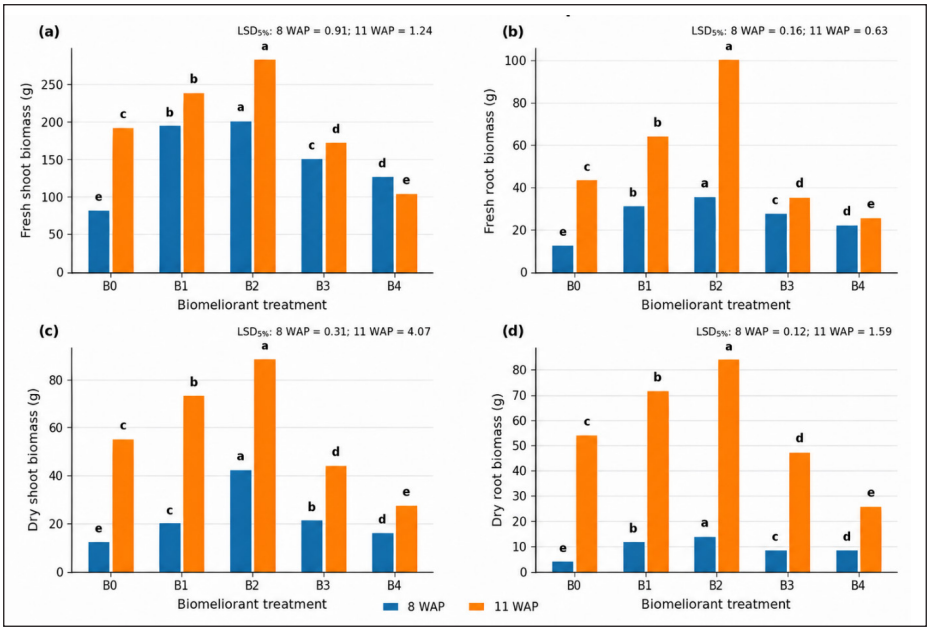


Figure 3. Effects of cattle manure and indigenous arbuscular mycorrhizal fungi (IAMF) treatments on plant biomass: (a) fresh shoot biomass, (b) fresh root biomass, (c) dry shoot biomass, and (d) dry root biomass at 8 and 11 weeks after planting (WAP). Different lowercase letters above the bars indicate significant differences among treatments within the same observation time according to the least significant difference (LSD) test at the 5% significance level ($P < 0.05$). Statistical comparisons were performed separately at each observation time

contrast with B3 and B4 carries no information about additivity or interaction, and B2 is best understood as the most favorable treatment for these sandy-soil conditions rather than an optimum in any general sense.

Effects of Bioameliorants on Fresh and Dry Biomass of Sweet Corn

Plot-level biomass at harvest followed the same ordering as the late-season component data (Figure 4). B2 reached 6.43 kg plot^{-1} fresh and 4.57 kg plot^{-1} dry, with B1 statistically comparable; against the control, these are increases of 11.6% and 77.8%. Figures 3 and 4 are complementary rather than duplicative, the former covering shoot and root components at 8 and 11 WAP and the latter total plot biomass at harvest. The much larger relative gain in dry than in fresh biomass again points to dry matter accumulation, which is consistent with reports that native AMF inoculation raises maize dry biomass along with tissue P and K (Bhupenchandra et al., 2025). The physiological steps behind it were not isolated in this experiment.

AMF are known to affect nutrient acquisition, photosynthetic performance, and carbon allocation, and recent maize work shows those responses varying considerably with environmental and nutrient conditions (Ran et al., 2024). None of them was quantified here.

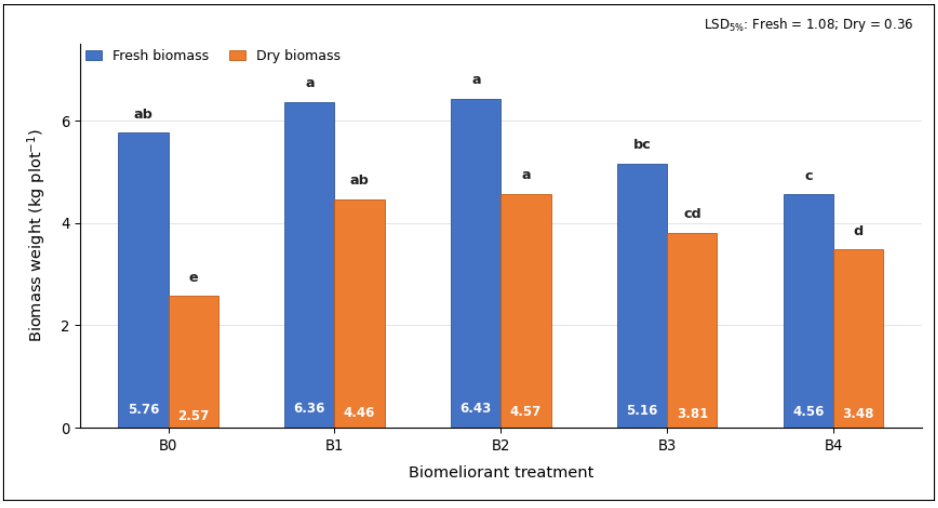


Figure 4. Effects of cattle manure and indigenous arbuscular mycorrhizal fungi (IAMF) treatments on total plot-level fresh and dry biomass of sweet corn at harvest. Different lowercase letters above the bars indicate significant differences among treatments within each biomass category according to the least significant difference (LSD) test at the 5% significance level ($P < 0.05$). Statistical comparisons were performed separately for fresh and dry biomass

The biomass result under B2 is reported as a treatment effect that coincided with favorable nutrient and mycorrhizal conditions, while the physiological route remains a literature-supported suggestion rather than a finding of this study.

B2 also accumulated more dry biomass than B3 or B4, so the combined formulations did not reliably out-produce IAMF alone under these conditions. Differences in nutrient supply, in mycorrhizal development, or in other treatment-specific factors may lie behind the gap, but none was tested directly, and the non-factorial structure again rules out any reading in terms of additive or interactive effects. The safest interpretation is that the evaluated formulations differed, not that a particular mechanism has been identified.

Effects of Bioameliorants on Sweet Corn Yield

IAMF at 3 t ha^{-1} without cattle manure (B2) gave the highest fresh ear weight (385.93 g plant^{-1}), dry ear weight (269.77 g plant^{-1}), and fresh ear yield (6.90 kg plot^{-1}), and yield components differed significantly among treatments at harvest (Table 4). For fresh ear yield, corrected mean separation placed B2 (6.90 kg plot^{-1}; a) with B1 (6.10 kg plot^{-1}; ab), the 0.80 kg plot^{-1} gap between them falling below the verified LSD of 1.21 kg plot^{-1}. B2 did exceed B4 (5.20 kg plot^{-1}; bc), B3 (4.73 kg plot^{-1}; c), and B0 (4.23 kg plot^{-1}; c) significantly. B2 was thus highest numerically but indistinguishable from B1, and taken as a group the yield components gave their most consistent response under B2 in this sandy soil.

Table 4
Effects of cattle manure and indigenous arbuscular mycorrhizal fungi (IAMF) treatments on fresh ear weight (FEW), dry ear weight (DEW), and fresh ear yield (FEYP) of sweet corn at harvest

Treatment	FEW	DEW	FEYP
B0: Control	148.79e	81.79e	4.23c
B1: 10 t ha^{-1} CM	319.75b	208.54b	6.10ab
B2: 3 t ha-1 IAMF	385.93a	269.77a	6.90a
B3: 5 t ha^{-1} CM + 1.5 t ha^{-1} IAMF	187,73d	108.64d	4.73c
B4: 10 t ha^{-1} CM + 3 t ha^{-1} IAMF	189.79c	131.67c	5.20bc
LSD 5%	1.22	1.14	1.21

Note. Means followed by the same letter are not significantly different according to the LSD test at the 5% significance level ($P < 0.05$). IAMF = indigenous arbuscular mycorrhizal fungi; CM = cattle manure

Yield under B2 followed its earlier performance in soil nutrient status, nutrient uptake, and mycorrhizal development: the highest soil total N and available P, the highest plant N and P uptake, 2,335.33 spores 100 g^{-1} soil and 89% root colonisation at 6 WAP, then high biomass and the largest ear yield. These responses are closely associated but causally unresolved. The inoculum came with a soil-cattle-manure carrier and no carrier-only treatment was run, so AMF activity and carrier-derived nutrient or organic-matter effects cannot be separated, and the B2 result belongs to the complete MAA01 formulation. Comparable outcomes have been reported in maize, where native AMF improved nutrient acquisition and productivity to a degree that depended on how AMF and nutrient inputs were combined.

Combined treatments did not out-yield the IAMF-only treatment. Fresh ear yield stood at 6.90 kg plot^{-1} under B2 against 4.73 kg plot^{-1} under B3 and 5.20 kg plot^{-1} under B4, and both combined treatments showed lower spore density and colonisation. Here again the non-factorial structure forbids any statement about additive or interactive effects between cattle manure and IAMF; the numbers establish only that more amendment did not dependably mean more yield. Nutrient supply and growing conditions weigh heavily on AMF performance, and field data show the yield and nutrient benefits shifting a good deal with the fertilisation regime (Akpodé et al., 2025). Among the treatments tested, then, B2 produced the best yield response, which is an argument for getting the formulation right rather than for raising inputs.

Morphological Characteristics of Bioameliorant Formulations

Surface character differed among the formulations, as both visual inspection and SEM at 1000× made clear (Figure 5): roughness varied, as did particle arrangement, compactness, and the extent of visible pores and voids. Organic and biologically derived amendments are commonly heterogeneous in just this way (Leifheit et al., 2014). What these images

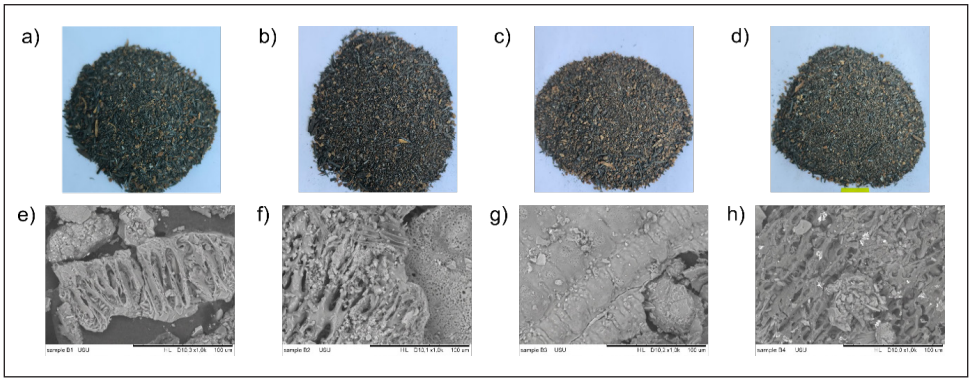


Figure 5. Macroscopic appearance (top row) and scanning electron microscopy (SEM) images at 1000× magnification (bottom row) of the bioameliorant formulations: (a,e) B1, 10 t ha^{-1} cattle manure (CM); (b,f) B2, 3 t ha^{-1} indigenous arbuscular mycorrhizal fungi (IAMF); (c,g) B3, 5 t ha^{-1} CM + 1.5 t ha^{-1} IAMF; and (d,h) B4, 10 t ha^{-1} CM + 3 t ha^{-1} IAMF

offer is description. Soil aggregation, microbial activity, nutrient availability, and pore-size distribution are not quantified by them, and Figure 5 ought to be read for the surface and microstructural features it actually records rather than as evidence bearing on nutrient supply or agronomic value.

SEM-EDX Characterisation of Elemental Composition in Bioameliorant Formulations

Elemental composition separated the formulations under SEM-EDX (Figure 6; Table 5). Oxygen accounted for the largest detected fraction in B1-B4, between 39.44 and 40.04 Mass%, and silicon was prominent as well. Nitrogen ran from 2.28 to 4.36%, potassium from 2.2 to 2.40%, calcium from 1.42 to 1.94%, magnesium from 0.48 to 0.58%, phosphorus

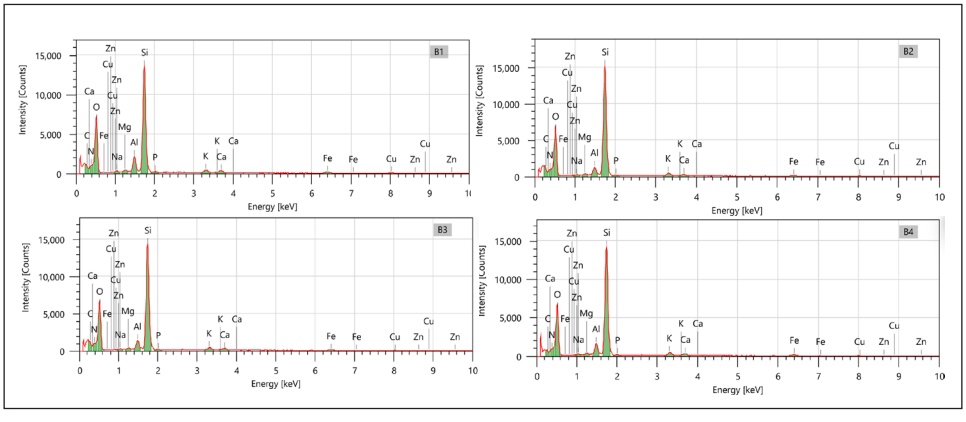


Figure 6. SEM-EDX spectra showing the elemental composition of the bioameliorant formulations: (B1) 10 t ha^{-1} cattle manure; (B2) 3 t ha^{-1} indigenous arbuscular mycorrhizal fungi (IAMF); (B3) 5 t ha^{-1} cattle manure + 1.5 t ha^{-1} IAMF; and (B4) 10 t ha^{-1} cattle manure + 3 t ha^{-1} IAMF

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Table 5

Elemental composition of the bioameliorant formulations (B1-B4) determined by SEM-EDS, expressed as mass percentage (Mass%) and atomic percentage (Atom%)

Element	Massa %				Atom %			
	B1	**B2**	**B3**	**B4**	**B1**	**B2**	**B3**	**B4**
C	nd	2.32 ± 0.19	1.46 ± 0.16	nd	nd	4.09 ± 0.33	2.58 ± 0.28	nd
N	2.83 ± 0.28	3.73 ± 0.31	4.36 ± 0.34	2.28 ± 0.26	4.43 ± 0.43	5.64 ± 0.47	6.60 ± 0.51	3.58 ± 0.41
O	40.04 ± 0.58	39.73 ± 0.59	39.77 ± 0.60	39.44 ± 0.59	54.91 ± 0.79	52.57 ± 0.77	52.79 ± 0.79	54.27 ± 0.81
Na	0.68 ± 0.07	0.35 ± 0.05	0.47 ± 0.06	0.60 ± 0.07	0.65 ± 0.07	0.33 ± 0.05	0.44 ± 0.05	0.58 ± 0.06
Mg	0.58 ± 0.05	0.48 ± 0.05	0.57 ± 0.05	0.53 ± 0.05	0.53 ± 0.05	0.41 ± 0.04	0.50 ± 0.05	0.48 ± 0.05
Al	5.35 ± 0.14	2.83 ± 0.10	3.18 ± 0.11	4.06 ± 0.13	4.35 ± 0.12	2.22 ± 0.08	2.50 ± 0.09	3.31 ± 0.10
Si	37.81 ± 0.38	40.25 ± 0.38	39.58 ± 0.38	41.54 ± 0.40	29.53 ± 0.30	30.33 ± 0.29	29.93 ± 0.29	32.57 ± 0.32
P	0.42 ± 0.05	0.33 ± 0.05	0.44 ± 0.05	0.42 ± 0.05	0.30 ± 0.04	0.22 ± 0.03	0.30 ± 0.04	0.30 ± 0.04
K	2.24 ± 0.12	2.24 ± 0.12	2.33 ± 0.12	2.40 ± 0.12	1.26 ± 0.07	1.21 ± 0.06	1.26 ± 0.06	1.35 ± 0.07
Ca	1.94 ± 0.11	1.42 ± 0.10	1.75 ± 0.11	1.71 ± 0.11	1.06 ± 0.06	0.75 ± 0.05	0.93 ± 0.06	0.94 ± 0.06
Fe	3.95 ± 0.27	2.73 ± 0.22	2.83 ± 0.23	3.95 ± 0.28	1.55 ± 0.11	1.03 ± 0.08	1.08 ± 0.09	1.56 ± 0.11
Cu	3.65 ± 0.38	3.38 ± 0.37	2.77 ± 0.34	2.96 ± 0.36	1.26 ± 0.13	1.13 ± 0.12	0.92 ± 0.11	1.03 ± 0.12
Zn	0.50 ± 0.21	0.22 ± 0.16	0.50 ± 0.21	0.12 ± 0.16	0.17 ± 0.07	0.07 ± 0.05	0.16 ± 0.07	0.04 ± 0.05
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Note. Values represent the relative Mass% and Atom% of the complete set of quantified elements detected by SEM-EDX in each bioameliorant formulation. The reported elements include C, N, O, Na, Mg, Al, Si, P, K, Ca, Fe, Cu, and Zn, where detected. The Mass% and Atom% values for each formulation were normalised by the EDX software to a total of 100.00%. Elemental quantification was performed using the standardless ZAF method. Values following ± represent the analytical uncertainty reported by the EDX software. “nd” indicates that the element was not detected above the analytical detection capability under the measurement conditions used

from 0.33 to 0.44%, and zinc from 0.12 to 0.50%, with sodium (Na), aluminum (Al), iron (Fe), and copper (Cu) also present. A carbon signal appeared in B2 at 2.32 Mass% and in B3 at 1.46 Mass%, but nothing detectable in B1 or B4 under the conditions used. The largest nitrogen and phosphorus fractions, 4.36% and 0.44%, belonged to B3; the largest potassium fraction, 2.40%, to B4. Full Mass% and Atom% values, normalised to 100% within each formulation, appear in Table 5. Local composition, then, clearly differed from one material to the next. What EDX is silent on is how much of any element will be transformed, released, cycled, dissolved, or taken up, which is why these proportions describe the materials and go no further.

Whether an element picked up by SEM-EDX matters to a crop turns on whether it becomes available for uptake, not on the share it occupies in the material. EDX interrogates selected regions of a specimen, and Mass% and Atom% outputs describe those regions and only those. Solubility, chemical release, and the size of the plant-accessible pool fall outside what the technique can establish (Ali et al., 2023). Our elemental data accordingly characterise the formulations without saying anything about their capacity to feed a crop.

B2 illustrates the point. Its EDX-derived proportions of N, P, and K were not the highest of the set, yet among the treatments examined it produced the strongest overall response in soil fertility and crop performance. B3 and B4, holding more of several detected elements, did not match it. Local elemental concentration, in other words, predicts nutrient accessibility and plant response poorly, a point Yu et al., (2024) also make. The two kinds of measurement are answering different questions: EDX describes the material, whereas soil fertility, plant nutrient uptake, AMF colonisation, biomass, and yield describe what became of it in the field.

Elemental Composition of Bioameliorant Formulations

The full elemental profile of the four formulations, together with the analytical uncertainty reported by the instrument, is set out in Table 5. Oxygen dominated throughout, running from 39.44 Mass% in B4 to 40.04 Mass% in B1 and, in atomic terms, from 52.57% in B2 to 54.91% in B1. Nitrogen spanned 2.28 to 4.36 Mass%, highest in B3 at 4.36 ± 0.34 Mass% (6.01 ± 0.51 Atom%), followed by B2 at 3.73 ± 0.31 Mass% (5.64 ± 0.47 Atom%), and lowest in B4 at 2.28 ± 0.26 Mass% (3.58 ± 0.41 Atom%).

Of the remaining elements, phosphorus occupied 0.33 to 0.44 Mass% and peaked in B3, whereas the largest potassium fraction, 2.40 Mass%, turned up in B4. Magnesium hardly varied at all, 0.48 to 0.58 Mass%, and calcium reached its maximum of 1.94 Mass% in B1. Zinc remained low across the set at 0.12 to 0.50 Mass%. Carbon registered at 2.32 Mass% in B2 and 1.46 Mass% in B3 and fell below detection in B1 and B4. Since EDX sensitivity differs by element and is at its poorest for light elements such as carbon and nitrogen, an absent carbon signal indicates that the method failed to detect carbon, not that the material contained none.

What EDX returns is local elemental abundance and elemental association, and its quantitative output is shaped by analytical conditions, matrix effects, element-specific sensitivity, and other instrumental factors (Newbury & Ritchie, 2015). Solubility, chemical speciation, and plant-available pools are not measured. The mass fractions given here are compositional characteristics of the bioameliorant formulations, and should be read in that light alone.

Elemental composition and field performance did not line up. B3 carried the most phosphorus and B4 the most potassium, yet neither matched B2 in soil fertility, plant N and P acquisition, mycorrhizal development, biomass production, or yield. Abundance in a small analysed region cannot, by itself, explain how a formulation performs; what reaches the plant depends on release, transformation, solubilisation, and the reactions occurring among soil, roots, and microorganisms. Similar mismatches in earlier amendment studies make the same case for pairing SEM-EDX characterisation with independent soil and plant assessments (Aumtong et al., 2026). In this trial the favorable showing of B2 coincided with better soil nutrient conditions, mycorrhizal indicators, nutrient uptake, biomass, and yield: associated changes that may reflect interactions among soil properties, AMF, and plant development, but that do not by themselves establish cause.

CONCLUSION

The five bioameliorant treatments produced significant differences in soil fertility, mycorrhizal indicators, plant nutrient acquisition, biomass production, and sweet corn yield on sandy soil, confirmed by ANOVA and LSD comparison at the 5% significance level. B2, 3 t ha^{-1} IAMF inoculum with no cattle manure, improved the widest range of measurements. Against the untreated control it raised soil total N, available P, plant N and P uptake, AMF spore density, and root colonisation; it supported strong vegetative growth and biomass accumulation; and it recorded the highest fresh ear weight (385.93 g $plant^{-1}$), dry ear weight (269.77 g $plant^{-1}$), and fresh ear yield (6.90 kg $plot^{-1}$), gains of 159.4%, 229.8%, and 63.1% over B0. Fresh ear yield under B2 was statistically similar to B1 but significantly above B0, B3, and B4 under the corrected LSD comparisons. The combined CM-IAMF formulations offered no consistent advantage over B2 in mycorrhizal development, biomass, or yield. Because the treatments sat in a non-factorial randomised complete block design, those differences describe the particular amendment combinations tested and cannot be taken as additive or interactive effects. The MAA01 inoculum also included carrier material, and without a carrier-only control the biological contribution of the fungi cannot be separated from what the carrier supplied. SEM-EDX showed, in addition, that local elemental abundance in the formulations bore no straightforward relationship to the soil and plant responses that followed. B2 was the best of the treatments evaluated on this sandy soil, while the manure-IAMF mixtures behaved differently in

ways that should not be read as factorial interactions. For a single site in a single season, 3 t ha^{-1} IAMF inoculum gave the most consistently favorable result; it should not be treated as a generally optimal rate, given the missing carrier-only control and the absence of direct measurements of broader soil biological activity. Confirming its value and its wider applicability will require trials at more locations and across more seasons, with the appropriate controls and biological assessments in place.

IMPLICATIONS OF THE STUDY

The practical weight of this trial lies in the rates. Three tonnes per hectare of IAMF inoculum matched ten tonnes per hectare of cattle manure in fresh ear yield (6.90 against 6.10 kg plot^{-1}, a gap inside the LSD) while exceeding it in soil total N, available P, plant N and P uptake, spore density, and root colonisation. For smallholders on the sandy drylands of Lombok and comparable parts of West Nusa Tenggara, where manure is bulky, seasonally scarce, and costly to cart to the field, a roughly 70% reduction in the mass of material that must be moved and incorporated is not a trivial agronomic detail. It also matters that every plot received only half the locally recommended rate of urea and NPK Phonska: these responses were obtained under reduced mineral input.

Second, the results argue against input stacking. The two combined formulations (including B4, which carried the full 10 t ha^{-1} of manure alongside the full 3 t ha^{-1} of inoculum) were weakest on mycorrhizal development and among the weakest on yield. Within the range tested, which formulation was applied mattered more than how much amendment was applied, and that is a cheaper message to act on than a recommendation to raise rates.

Third, MAA01 was built from AMF populations of regional origin and multiplied by pot culture on maize, a procedure requiring no specialised facility. Its performance supports treating local AMF germplasm from NTB dryland soils as a propagable resource rather than a purchased input.

Finally, the SEM-EDX results carry a methodological implication beyond this crop. Local elemental abundance ranked the formulations in one order and field performance in another: B3 held the most nitrogen and phosphorus, B4 the most potassium, and neither approached B2 in the field. Elemental characterisation describes what a material contains, not what a crop can obtain from it, and should accompany soil and plant assessment rather than substitute for it.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The present findings should be read within the scope of the design used. MAA01 is a carrier-based formulation in which propagules are held in a substrate of soil and sterilised cattle manure, and no carrier-only or inactivated-inoculum control was included, so the responses under B2 are attributed to the complete formulation rather than to the fungi

alone. Treatments were arranged as a single factor, so the comparisons describe the five formulations as applied rather than the separate effects of cattle manure and IAMF. Mycorrhizal development was assessed morphologically on one date and reflects the overall AMF population rather than the introduced isolate specifically, and soil characterisation was confined to total N and available P at 6 WAP. The trial covered one site, one season, one cultivar, and three blocks, and the results accordingly describe sandy soil conditions at Ampenan during May-July 2026.

These boundaries point to several directions worth pursuing. (1) Including a sterilised inoculum and a carrier-only control would allow the fungal contribution to be distinguished from that of the carrier. (2) A factorial arrangement of manure and inoculum rates, with a dose-response series around 3 t ha^{-1}, would test additivity and identify an optimum rate. (3) Molecular identification and community profiling would confirm the identity of MAA01 and track its establishment against the resident community. (4) Sampling on several dates, including post-harvest, together with phosphorus fractionation and broader soil characterisation (organic matter, CEC, pH, exchangeable K), would show how the response develops and whether it persists into a following season; the gain in available P under B2 relative to the phosphorus the carrier itself could supply makes mobilisation of native soil P a particularly useful hypothesis to test. (5) Measurements of extraradical hyphal length, hyphal nutrient transfer, phosphatase activity, and root architecture, or isotope labelling, would help identify the mechanism involved. (6) Multi-location and multi-season trials across the dryland agroecologies of West Nusa Tenggara, with additional cultivars and a range of fertiliser levels, alongside a partial budget comparing inoculum production against manure purchase and transport, would establish how widely the 3 t ha^{-1} rate applies and whether it is economically attractive.

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