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Contribution of Arbuscular Mycorrhizal Fungi to Improving Maize Growth and Yield in the Low-Fertility Ultisols of Thailand

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Abstract

Restrictions in crop production in Ultisols are primarily due to low soil fertility, which limits their capacity to supply sufficient nutrients for plant growth. Importantly, arbuscular mycorrhizal fungi (AMF) can play a role in enhance nutrient availability for plants. This study aims to evaluate the effects of AMF inoculation combined with chemical fertilisation on maize growth and yield in three soil series of Ultisols. A pot experiment was performed with a 2 × 3 factorial CRD with five replications. Two factors were studied: (1) AMF (*Glomus* sp.) (non-AMF and AMF inoculation) and (2) rates of chemical fertiliser (0, 50, and 100% of the recommended fertiliser rate for maize, CF). The results showed that AMF significantly enhanced the growth and yield of maize at all CF rates across all soil series. Total biomass and grain yield following the AMF treatment were markedly higher than after the non-AMF treatment. Likewise, AMF significantly improved the photosynthetic physiology and NPK content of maize. The CF rate had a negative impact on AMF root colonisation, and the AMF efficiency also decreased as the CF rate increased. The relative mycorrhizal dependency (RMD) on maize growth and yield were the highest at 0% CF, with averages of 34.49% and 52.35%, but decreased to 7.43% and 8.73% at 100% CF, respectively. However, the RMD of maize growth and yield remained positive for soil series. These findings suggest that AMF are an effective means of supporting maize cultivation in Ultisols.

Keywords: arbuscular mycorrhizal fungi; maize; Ultisols

1. Introduction

Low-fertility soils are the product of a primary type of soil degradation that severely impacts crop cultivation. Low-fertility soils classified as Ultisols are widespread in tropical savanna climates, such as in Thailand [1], with Ultisols covering approximately 40% of Thailand's total agricultural area [2]. Due to the high degree of soil weathering in this climate zone, these soils are characterised by poor nutrient availability, low nutrient-holding capacity, high nutrient leaching, and extreme acidity [3]. These conditions significantly constrain agricultural production, resulting in poor plant growth and low crop yields. Thus, low-fertility soils represent a severe form of soil degradation, posing a significant threat to future food security. Consequently, cultivating crops in low-fertility Ultisols requires an integrated approach that involves both fertiliser application and consideration of soil properties [4].

AMF are outstanding at increasing nutrient absorption in plants. These fungi form a mutualistic symbiotic relationship with higher plants. Approximately 80% of all plant species form this

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association, with the exceptions being members of the Brassicaceae and Chenopodiaceae families. Both the plants and fungi benefit from this symbiosis. The external fungal hyphae absorb nutrients from the soil and transport them to specialised exchange structures (arbuscules) within the cortical cells of the plant roots. The nutrients are then transferred to the plant. In return, the fungi receive carbon compounds, primarily sugars, from the plant via the same exchange structures [5]. Thus, AMF are a vital conduit, facilitating the transfer of soil nutrients to the plant through mutualistic symbiosis, ultimately enhancing the plant's nutrient uptake. Previous studies have demonstrated that AMF contribute significantly to the absorption of essential nutrients from the soil, including primary and secondary macronutrients and micronutrients [6–8]. Moreover, they play an indispensable role in retaining nutrients in the soil by reducing nutrient leaching, thereby improving fertilisation efficiency and increasing nutrient availability for plants [9–12]. These functions of AMF are highly advantageous for crops cultivated in Ultisols. This is particularly important given the challenges posed by soil acidity, significant leaching, and low cation exchange capacity, all of which hinder the accessibility of essential nutrients for plants in these soils [13]. Given the critical role of AMF in supporting plant nutrient availability, it is plausible that employing AMF in Ultisol cultivation would enhance soil productivity.

Thailand cultivates maize nationwide, but especially in the northern and northeastern regions where Ultisols are widely distributed [2]. Nutrient deficiency due to the low fertility of this soil is a typical limitation of cultivation, resulting in low growth and yield of maize. Farmers face higher chemical fertiliser costs, which reduce the country's economic competitive potential. However, a recent study by Agbodjato et al. [14] showed that AMF can significantly promote the growth and yield of maize under both pot and field experimental conditions. AMF play a crucial role in enhancing plant nutrient uptake [15]. AMF maize can grow better than non-AMF maize and has a reduced need for chemical fertiliser [16]. A study by Fall et al. [17] clearly indicated that AMF inoculation with 50% NPK mineral fertiliser significantly promoted maize growth and shoot NPK content compared to 100% NPK fertiliser alone. Therefore, AMF may solve the nutrient-related problems of Ultisols. This study aims to (1) evaluate the effects of AMF inoculation combined with site-specific fertiliser recommendations on the growth and yield of maize and (2) examine the efficiency of AMF application in maize cultivation in three Ultisol soil series. This study's outcomes are expected to benefit maize plantations on low-fertility Ultisols in Thailand and the surrounding region.

2. Materials and Methods

2.1. Soil Samples and Properties

The soils used in this study were classified as Ultisols [1,2], which are characteristic of the tropical savanna climate of Thailand. Three samples were collected from the top layer (0–20 cm) of soil at agricultural sites during the dry season of 2025. The Korat (Kt) soil series (Typic Kandiustults) was collected from Nong Krat Subdistrict, Dan Khun Thot District, Nakhon Ratchasima Province (15.364550° N, 101.659338° E), the Mabbon (Mb) soil series (Oxic Paleustults) was collected from Khao Hin Son Subdistrict, Phanom Sarakham District, Chachoengsao Province (13.76287° N, 101.49406° E), and the Pakthongchai (Ptc) soil series (Typic Peleustults) was collected from Lalom Mai Pattana Subdistrict, Chok Chai District, Nakhon Ratchasima Province (14.794504° N, 102.259356° E). The soil characteristics are presented in Table 1. The overall fertility of these soil series is classified as low [18].

Table 1. The initial physico-chemical properties of soil series classified as Ultisols.

Soil Physico-Chemical Properties	Soil Series of Ultisols		
	Korat	Mabbon	Pakthongchai
Texture [1/]	Loamy sand	Sandy loam	Loam
Sand (%)	72.2	60.8	41.3
Silt (%)	16.3	22.1	42.8
Clay (%)	11.5	17.1	15.9

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pH (1:1 H_2O)	5.8	5.1	5.6
Organic matter [2] (g.kg^{-1})	7.14	6.52	5.11
Available phosphorus [3] (mg P.kg^{-1})	8.28	5.16	8.64
Available potassium [4] (mg K.kg^{-1})	36.3	62.1	55.9
CEC [5] (cmol.kg^{-1})	6.5	10.4	8.2
Base saturation [6] (%)	28	32	30
Level of soil fertility	Low	Low	Low

[1] Pipette method; [2] Walkley and Black titration method; [3] Bray II extraction; [4] 1M NH_4OAc (pH 7.0) extraction; [5] CEC = cation exchange capacity, 1 M NH_4OAc saturation method. [6] 1M NH_4OAc method.

Plant debris was removed from the soil samples, which were air-dried in the shade and then sieved through a 2 mm mesh. The soils were homogenised and sterilised using an autoclave at 121 °C and 15 psi for 15 min to eliminate native AMF before their use in the experiment. This sterilised soil was tested on corn and found to have no AMF colonisation in the roots.

2.2. Materials

The AMF species (*Glomus* sp., KUSoil5), which was proven to be effective in maize production by Poomipan et al. [19], was provided by the Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok, Thailand. This AMF was isolated from maize-associated soils at the National Corn and Sorghum Research Centre (Pakchong soil series, Rhodic Kandiustox, 14.64227° N, 101.31517° E) and identified based on morphological characteristics and 18S rDNA sequence analysis by Na Bhadalung et al. [20] and Na Bhadalung [21]. The AMF spores were separated from the soil using the wet-sieving and decanting method [22], followed by the sucrose centrifugation method [23]. They were then propagated via single spore germination, using sorghum (*Sorghum bicolor* L.) as a host plant [24]. Sorghum was grown for 3 months in sterilised sand with a nutrient solution and watered daily with sterile distilled water [25]. After 3 months, the roots and sand were harvested to produce an AMF soil inoculum containing 30 spores per gram.

Chemical fertiliser was applied at rates determined by site-specific soil analysis for maize cultivation [26]. For the Korat and Pakthongchai soil series, fertiliser was used at a rate of 100-25-60 kg N-P_2O_5-K_2O/ha. For the Mabbon soil series, fertiliser was applied at a rate of 100-25-50 kg N-P_2O_5-K_2O/ha. As fertilisers, urea, triple super phosphate, and muriate of potash were used as required to provide nitrogen, phosphorus, and potassium, respectively.

2.3. Experimental Setup

The pot experiment was conducted from May to August 2025 at the Faculty of Science and Technology, Thammasat University, Pathum Thani, Central Thailand (14.07389° N, 100.60554° E). The average temperature inside the greenhouse during the plant growth period was 28–34 °C, and the average relative humidity was 75%.

The experiment was conducted with a 2 × 3 factorial completely randomised design (CRD) with five replicates. Two factors were studied: (1) AMF treatment, consisting of either no AMF (Non-AMF) or AMF (AMF) inoculation, and (2) three rates of site-specific chemical fertiliser (CF) recommendations for maize cultivation in Ultisols: 0 (0% CF), 50 (50% CF), and 100 (100% CF) %.

The surfaces of the pots and trays were sterilised by spraying them with 70% alcohol. Each pot was then filled with 15 kg of sterilised soil, with 30 pots prepared for each soil series. A five-centimetre-deep hole was dug in the centre of each pot. For the AMF treatment, 10 g of AMF soil inoculum was added per pot, while for the non-AMF treatment, 10 g of sterilised AMF soil inoculum was added to ensure uniform nutrient levels across all pots.

The maize hybrid used was Suwan 4452, which was obtained from the National Corn and Sorghum Research Centre, Faculty of Agriculture, Kasetsart University, Thailand. Maize seeds were surface-sterilised with 10% hydrogen peroxide (H_2O_2) for 10 min and then rinsed with sterile distilled

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water before planting. Five maize seeds were sown per pot, and the seedlings were thinned 14 days after planting (DAP) to retain one plant per pot.

Chemical fertiliser was applied to maize grown in the Korat and Pakthongchai soil series in two splits at 0 and 28 days after planting (DAP). The chemical fertiliser was applied at rates of 25-12.5-30 and 25-0-0 kg N-P_2O_5-K_2O/ha for the 50% CF treatment and at rates of 50-25-60 and 50-0-0 kg N-P_2O_5-K_2O/ha for the 100% CF treatment. For maize planted in the Mabbon soil series, fertiliser was also applied in two splits at 0 and 28 DAP. The chemical fertiliser was applied at rates of 25-12.5-25 and 25-0-0 kg N-P_2O_5-K_2O/ha for the 50% CF treatment and at rates of 50-25-50 and 50-0-0 kg N-P_2O_5-K_2O/ha for the 100% CF treatment. Throughout the experiment, the plants were watered adequately according to the requirements for maize, and manual pest and weed control was performed.

2.4. Data Collection and Analysis

During the growing stage, shoot height was measured using a tape measure, which was placed from the collar to the sheath of the last fully emerged leaf. The stem diameter was measured using a vernier calliper at 30, 45, and 60 DAP. The number of days to silking and 50% tasselling were recorded. The net photosynthetic rate, transpiration rate, and stomatal conductance were measured using a portable photosynthesis system (LI-COR 6400, Lincoln, NE, USA). The total chlorophyll relative content was measured using a versatile SPAD chlorophyll meter (SPAD-502, Minolta Camera Co., Ltd., Osaka, Japan). Measurements were taken from fully developed leaves at the fifth and sixth leaf positions from the bottom, with five points per leaf, between 9:00 A.M. and 11:00 A.M. when the maize plants reached the reproductive stage (60 DAP) [27].

During the harvesting stage at 120 DAP, the dry weight of shoots (leaves and stems), unhusked ears, and roots was measured after drying the samples in a hot air oven at 65 °C until a constant weight was achieved. Yield components were assessed in terms of ear size (width and length) and dry weight (husked ears and total grain). The maize yield, comprising grain yield at 14% moisture content and biological yield, was also measured. The percentage harvest index was then calculated as the ratio of grain yield at 14% moisture content to biological yield.

The mycorrhizal dependency, as defined by Gerdeman [28], was calculated to evaluate the effectiveness of the AMF in promoting plant growth and yield under specific levels of fertiliser management. A higher relative mycorrhizal dependency (RMD) indicates a greater dependence on mycorrhizae. The RMD can be calculated using the formula described by Plenchette et al. [29], as follows:

$$\text{RMD of maize growth (\%)} = \frac{\text{TDW of AMF plant} - \text{TDW of non AMF plant}}{\text{TDW of AMF plant}} * 100$$

$$\text{RMD of maize yield (\%)} = \frac{\text{TGY of AMF plant} - \text{TGY of non AMF plant}}{\text{TGY of AMF plant}} * 100$$

where TDW and TGY represent the total dry weight and total grain yield of maize, respectively.

Leaves and stems were finely ground and passed through a 0.2 mm sieve to determine the nutrient content of the maize shoots. Total nitrogen (N) was determined using the micro-Kjeldahl distillation method [30]. Total phosphorus (P) was analysed using the yellow vanadomolybdophosphoric acid colourimetric method with a UV spectrophotometer [31]. Total potassium (K) was measured using atomic absorption spectrometry [32].

Roots were randomly sampled at 10 g of fresh weight per sample. The roots were stained following the method employed by Philips and Hayman [33] and washed with water until clean, placed in a beaker, soaked in a 10% (*w*/*v*) KOH solution, heated at 90 °C for 20 min in a water bath, and then rewashed with water. The roots were acidified by soaking in a 2% (*v*/*v*) HCl solution at room temperature for five minutes, after which the HCl solution was discarded. The roots were then stained with 0.05% (*w*/*v*) trypan blue solution and heated again at 90 °C for 30 min in a water bath, after which excess stain was removed by storing the stained roots overnight in a lactic acid–glycerol–water solution (1:1:1, *v*/*v*/*v*). The stained roots were cut into 1 cm segments, and 20 of these segments were randomly selected and mounted on slides. AMF colonisation was assessed under a microscope

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following the method employed by Trouvelot et al. [34], and the colonisation percentage was calculated using the following formula:

$$\text{AMF root colonisation (\%)} = \frac{(95 * n5) + (70 * n4) + (30 * n3) + (5 * n2) + (1 * n1)}{N} * 100$$

where AMF root colonisation = the colonisation of plant roots by AMF; n5–n1 = number of root segments with >90%, 51–90%, 11–50%, <10%, and 0% colonisation, respectively; and N = total number of root segments evaluated.

After harvesting the maize, 100 g soil samples were randomly collected from the maize rhizosphere. AMF spores were separated from the soil using the wet-sieving–decanting method [22] and the sucrose centrifugation method [23] to evaluate the number of AMF spores in the soil.

2.5. Data Analysis

All data were subjected to analysis of variance (ANOVA) using F-tests to statistically assess the differences in means between groups. Differences among treatment means were compared using Duncan's multiple range test (DMRT) at the 0.05 probability level ($p \leq 0.05$).

3. Results

3.1. Effects of AMF Inoculation and Fertiliser Rate on Maize Growth

AMF inoculation and fertiliser rate had a significant impact on maize growth in all three soil series. In the Korat soil series, AMF inoculation combined with either 0% CF or 50% CF significantly increased shoot height and stem diameter at 30 and 60 DAP, as well as the dry weight of shoots and roots, compared to non-AMF inoculation at the same fertiliser rates. AMF inoculation also led to earlier tasselling and silking compared to non-AMF-inoculated maize under 0% CF and 50% CF treatment. However, when combined with 100% CF, AMF inoculation significantly increased the 30 DAP shoot height and the dry weight of shoots compared to fertiliser alone. However, AMF inoculation did not substantially enhance other growth parameters when applied with 100% CF (Table 2(a)). Similarly, in the Mabbon soil series, AMF inoculation enhanced shoot height at 30 and 60 DAP, increased stem diameter at 60 DAP, increased the dry weight of shoots and roots, and accelerated the number of days to tasselling and silking. These effects were particularly pronounced when AMF inoculation was combined with 0% CF and 50% CF rates. Furthermore, AMF inoculation combined with 100% CF significantly increased the 30 and 60 DAP shoot height and dry weight of shoots compared to 100% CF without AMF inoculation (Table 2(b)). Almost all the results were found to be the same as those of the Pakthongchai soil series, which showed that AMF inoculation in combination with 0% CF and 50% CF significantly enhanced the 30 and 60 DAP shoot height, 30 and 60 DAP stem diameter, and the dry weight of shoots and roots compared to non-AMF-inoculated maize. The AMF-inoculated maize also reached the tasselling and silking stages earlier than non-inoculated plants under the same fertiliser conditions. Similarly, AMF inoculation had an impact on some growth parameters when applied with 100% CF. At 100% CF, the 30 and 60 DAP shoot height and the dry weight of the shoots were higher in AMF maize than in non-AMF maize, but there was no effect on the other growth parameters (Table 2(c)). Overall, AMF inoculation increased the shoot dry weight at all three rates of CF. The dry weight of the root of AMF maize with 50% CF did not significantly differ compared to non-AMF maize with 100% CF. These results were found in all three soil series (Table 2(a)–(c)).

Table 2. Effect of AMF application and fertiliser rate on maize growth.

Treatment		Stem Height (cm)		Stem Diameter (mm)		Days of Tasselling (Days)	Days of Silking (Days)	Dry Weight (g plant^{-1})	
Fertiliser	**AMF**	**30 DAP**	**60 DAP**	**30 DAP**	**60 DAP**			**Shoot**	**Root**
				(a) Korat soil					
0% CF	**Non-AMF**	13.5 ^{d}	47.3 ^{e}	4.4 ^{e}	7.5 ^{d}	68 ^{a}	73 ^{a}	27.33 ^{f}	2.81 ^{d}
	AMF	21.4 ^{c}	61.1 ^{d}	7.1 ^{d}	11.2 ^{c}	62 ^{b}	66 ^{b}	43.98 ^{e}	6.88 ^{c}

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50% CF	**Non-AMF**	22.4 ^{c}	82.3 ^{c}	10.9 ^{c}	14.8 ^{b}	55 ^{c}	61 ^{c}	75.43 ^{d}	8.96 ^{b}
	AMF	32.8 ^{b}	127.4 ^{b}	14.1 ^{b}	17.9 ^{a}	54 ^{c}	59 ^{d}	85.22 ^{c}	11.22 ^{a}
100% CF	**Non-AMF**	25.4 ^{c}	192.9 ^{a}	16.4 ^{a}	18.6 ^{a}	52 ^{d}	54 ^{e}	95.58 ^{b}	11.62 ^{a}
	AMF	39.2 ^{a}	201.5 ^{a}	16.1 ^{a}	18.5 ^{a}	52 ^{d}	54 ^{e}	110.81 ^{a}	12.03 ^{a}
				F test					
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		**	**	**	**	**	**	**	*
				(b) Mabbon soil					
0% CF	**Non-AMF**	15.1 ^{d}	52.4 ^{e}	4.7	6.7 ^{d}	70 ^{a}	73 ^{a}	28.17 ^{f}	2.98 ^{d}
	AMF	21.2 ^{c}	69.9 ^{d}	7.1	11.6 ^{c}	63 ^{b}	64 ^{b}	40.43 ^{e}	6.83 ^{c}
50% CF	**Non-AMF**	23.7 ^{c}	78.9 ^{d}	11.6	13.3 ^{c}	57 ^{c}	63 ^{b}	75.14 ^{d}	9.39 ^{b}
	AMF	34.3 ^{b}	121.8 ^{c}	13.6	17.1 ^{b}	54 ^{d}	60 ^{c}	84.68 ^{c}	12.46 ^{a}
100%CF	**Non-AMF**	35.3 ^{b}	190.0 ^{b}	17.4	19.4 ^{a}	52 ^{e}	56 ^{d}	98.41 ^{b}	12.77 ^{a}
	AMF	40.7 ^{a}	200.2 ^{a}	17.7	18.2 ^{a}	51 ^{e}	54 ^{d}	112.13 ^{a}	13.04 ^{a}
				F test					
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		**	**	ns	**	*	**	**	*
				(c) Pakthongchai soil					
0% CF	**Non-AMF**	15.4 ^{d}	44.0 ^{f}	4.2 ^{e}	7.0 ^{d}	67 ^{a}	73 ^{a}	31.73 ^{f}	3.98 ^{d}
	AMF	22.5 ^{c}	59.9 ^{e}	6.9 ^{d}	9.7 ^{c}	61 ^{b}	66 ^{b}	45.10 ^{e}	6.51 ^{c}
50% CF	**Non-AMF**	23.8 ^{c}	83.0 ^{d}	10.6 ^{c}	14.2 ^{b}	56 ^{c}	61 ^{c}	74.48 ^{d}	9.28 ^{b}
	AMF	34.1 ^{b}	119.0 ^{c}	15.0 ^{b}	18.1 ^{a}	54 ^{c}	59 ^{d}	85.04 ^{c}	12.44 ^{a}
100%CF	**Non-AMF**	34.8 ^{b}	186.1 ^{b}	16.9 ^{a}	18.2 ^{a}	52 ^{d}	55 ^{e}	101.07 ^{b}	13.09 ^{a}
	AMF	40.5 ^{a}	209.7 ^{a}	17.1 ^{a}	19.1 ^{a}	51 ^{d}	54 ^{e}	115.81 ^{a}	12.82 ^{a}
				F test					
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		**	**	**	*	**	**	**	*

Means with different letters in a column are significantly different at $p \leq 0.05$ by Duncan's multiple range test (DMRT). ns = not significantly different; * = significantly different at $p \leq 0.05$; ** = significantly different at $p \leq 0.01$; DAP = days after planting; CF = recommended rate of chemical fertiliser; AMF = arbuscular mycorrhizal fungi.

3.2. Effects of AMF Inoculation and Fertiliser Rate on Maize Yield

AMF inoculation and fertiliser rate had a significant interactive effect on maize yield parameters. In the Korat soil series, AMF inoculation combined with all CF rates significantly increased the dry weight of unhusked and husked ears, ear length, and biological yield compared to CF application alone. At 0% CF and 50% CF, AMF inoculation increased the dry grain weight, ear width, and grain yield at 14% moisture content compared to maize grown without AMF inoculation, but AMF inoculation had no effect when combined with 100% CF (Table 3(a)). Similarly, in the Mabbon soil series, AMF inoculation combined with all CF rates significantly increased the dry weight of unhusked and husked ears, the dry grain weight, ear length, biological yield, and grain yield at a 14% moisture content compared to CF application alone. At 0% and 50% CF, AMF inoculation increased ear width compared to maize without AMF treatment, but had no effect when combined with 100% CF (Table 3(b)). AMF inoculation produced clear results in the Pakthongchai soil series. AMF inoculation combined with CF at all rates significantly increased all maize yield parameters. The ear dry weight, grain dry weight, ear size, and maize yield of AMF maize were higher than those of non-AMF maize at all CF application rates (Table 3(c)). In all three soil series, AM inoculation affected the harvest index when applied with 0% CF and 50% CF but not when used with 100% CF (Table 3(a)–(c)). Therefore, AMF inoculation improved maize yield across all three soil series despite the fertiliser rate affecting AMF effectiveness.

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Table 3. Effect of AMF application and fertiliser rate on maize yield.

Treatment		Dry Weight of Ear (g plant^{-1})		Dry Weight of Grain (g plant^{-1})	Size of Ear (mm)		Maize Yield (g plant^{-1})		Harvest Index (%)
Fertiliser	AMF	Unhusked Ear	Husked Ear		Width	Length	Biological Yield	Grain Yield 1/	
(a) Korat soil									
0% CF	Non-AMF	4.44 f	2.98 f	2.44 e	19.2 d	83.4 f	30.14 f	2.78 e	0.09 e
	AMF	10.28 e	7.77 e	5.60 d	27.2 c	91.2 e	50.86 e	6.38 d	0.13 d
50% CF	Non-AMF	23.77 d	19.93 d	13.35 c	27.2 c	105.7 d	84.38 d	15.22 c	0.18 c
	AMF	31.64 c	29.45 c	21.89 b	32.2 b	124.0 c	96.44 c	24.95 b	0.26 b
100% CF	Non-AMF	44.35 b	42.73 b	35.71 a	37.3 a	132.1 b	109.80 b	40.71 a	0.37 a
	AMF	49.92 a	47.20 a	38.08 a	37.7 a	138.4 a	122.83 a	43.41 a	0.35 a
F test									
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		*	**	**	**	*	*	**	**
(b) Mabbon soil									
0% CF	Non-AMF	5.60 f	3.25 f	2.37 f	17.3 e	49.2 f	31.16 f	2.70 f	0.09 d
	AMF	9.86 e	6.86 e	5.15 e	25.2 d	60.6 e	47.26 e	5.87 e	0.13 d
50% CF	Non-AMF	25.38 d	22.11 d	18.60 d	31.6 c	71.8 d	84.53 d	21.20 d	0.25 c
	AMF	30.67 c	30.45 c	26.25 c	36.4 b	113.6 c	97.13 c	29.92 c	0.31 b
100% CF	Non-AMF	47.13 b	45.91 b	39.64 b	42.3 a	125.7 b	115.19 b	45.19 b	0.39 a
	AMF	52.63 a	49.68 a	43.99 a	42.7 a	136.9 a	125.17 a	50.15 a	0.40 a
F test									
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		*	**	*	**	**	**	**	**
(c) Pakthongchai soil									
0% CF	Non-AMF	7.66 f	4.86 f	3.86 f	21.8 f	67.5 f	35.71 f	4.40 f	0.12 e
	AMF	11.14 e	9.05 e	7.29 e	26.0 e	85.9 e	51.61 e	8.31 e	0.16 d
50% CF	Non-AMF	23.92 d	21.11 d	16.60 d	32.6 d	97.3 d	83.77 d	18.92 d	0.23 c
	AMF	32.87 c	29.57 c	24.24 c	36.3 c	127.9 c	97.48 c	27.64 c	0.28 b
100% CF	Non-AMF	45.92 b	43.59 b	37.77 b	42.3 b	136.4 b	116.16 b	43.05 b	0.37 a
	AMF	50.88 a	47.45 a	41.96 a	45.9 a	145.9 a	128.63 a	47.83 a	0.37 a
F test									
Fertiliser		**	**	**	**	**	**	**	**
AMF		**	**	**	**	**	**	**	**
Fertiliser x AMF		*	**	*	*	**	*	**	**

1/ Grain yield at a 14% moisture content. Refer to Table 2 for the meaning of the abbreviations. Means with different letters in a column are significantly different at $p \leq 0.05$ by DMRT. * = significantly different at $p \leq 0.05$; ** = significantly different at $p \leq 0.01$.

3.3. Relative Mycorrhizal Dependency on Maize Growth and Yield According to Fertiliser Rate

AMF significantly enhanced maize growth and yield, as indicated by positive RMD values across all soil series. However, the RMD values decreased as the CF rates increased.

The RMD of maize growth was highest when no chemical fertiliser (0% CF) was applied. Maize grown in the Korat, Mabbon, and Pakthongchai soil series had RMD values of 40.68%, 32.42%, and 30.36%, respectively. In contrast, the RMD for maize grown with chemical fertiliser application at rates of 50% CF and 100% CF was significantly lower than that without fertiliser (0% CF), with values ranging from 13.46 to 14.30% and 6.25 to 9.18%, respectively (Table 4).

The RMD of maize yield was also highest in the absence of chemical fertiliser (0% CF). Maize yield in the Korat, Mabbon, and Pakthongchai soil series exhibited RMD values on yield of 55.96%, 54.04%, and 47.04%, respectively. Following these were the RMD values for maize yield with chemical fertiliser application at a rate of 50%, where maize yield in the Korat, Mabbon, and Pakthongchai soil series was 38.84%, 29.21%, and 30.84%, respectively, and the lowest RMD values

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for maize yield of 5.38%, 10.84%, and 9.96% were observed for these soil series, respectively, with 100% CF application (Table 4).

Table 4. Relative mycorrhizal dependency (RMD) on growth and yield of maize, AMF root colonisation, and soil AMF spore number of AMF maize according to fertiliser rate.

Treatment	RMD of Maize Growth (%)	RMD of Maize Yield (%)	AMF Root Colonisation (%)	Soil AMF Spore (Spores/100 g)
		(a) Korat soil		
0% CF	40.68 [a]	55.96 [a]	67.27 [a]	808 [a]
50% CF	13.46 [b]	38.84 [b]	52.72 [b]	933 [a]
100% CF	6.25 [c]	5.38 [c]	37.32 [c]	596 [b]
F test	**	**	**	**
		(b) Mabbon soil		
0% CF	32.42 [a]	54.04 [a]	65.30 [a]	785 [a]
50% CF	14.30 [b]	29.21 [b]	54.27 [b]	835 [a]
100% CF	6.85 [c]	10.84 [c]	39.54 [c]	601 [b]
F test	**	**	**	*
		(c) Pakthongchai soil		
0% CF	30.36 [a]	47.04 [a]	69.46 [a]	912 [a]
50% CF	13.95 [b]	30.84 [b]	48.43 [b]	865 [a]
100% CF	9.18 [c]	9.96 [c]	36.88 [c]	532 [c]
F test	**	**	**	**

Means with different letters in a column are significantly different at $p \leq 0.05$ by DMRT. * = significantly different at $p \leq 0.05$; ** = significantly different at $p \leq 0.01$.

3.4. AMF Root Colonisation and Soil AMF Spore Numbers Affected by Fertiliser Rate

The percentage of AMF root colonisation was the highest at 0% CF (by a significant difference) and the lowest at 100% CF. Percentages of AMF root colonisation of 67.27%, 65.30%, and 69.46% of AMF were observed under 0% CF treatment in the Korat, Mabbon, and Pakthongchai soil series, respectively, whereas percentages of AMF root colonisation of 52.72%, 54.27%, and 48.43% were observed under 50% CF treatment in these soil series, respectively, and these percentages were reduced to 37.32%, 39.54%, and 36.88% under 100% CF in these soil series, respectively (Table 4). The increased fertiliser rate resulted in a decrease in AMF root colonisation. Fertilisation with 100% CF resulted in an average reduction in AMF root colonisation of approximately 43% across all soil series compared to that of 0% CF.

The soil AMF spore number was significantly higher under 0% CF and 50% CF than under 100% CF. There were 808, 785, and 912 spores/100 g of soil under the 0% CF treatment and 933, 835, and 865 spores/100 g of soil under the 50% CF treatment in the Korat, Mabbon, and Pakthongchai soil series, respectively. However, the soil AMF spore number decreased under the 100% CF treatment to 596, 601, and 532 spores/100 g of soil in the Korat, Mabbon, and Pakthongchai soil series, respectively (Table 4). Similarly, the increased fertiliser rate decreased the soil AMF spore number.

3.5. Correlation Between AMF Root Colonisation on RMD of Maize Growth and Yield

AMF root colonisation and the RMD of maize growth were significantly positively correlated at $p \leq 0.01$, with a high correlation level (0.701). Similarly, AMF root colonisation and the RMD of maize yield were significantly positively correlated at $p \leq 0.01$, with a moderate correlation (0.673). The correlation analysis revealed a clear link: a higher degree of AMF root colonisation is associated with enhanced RMD of maize growth and yield. Conversely, lower AMF root colonisation tends to result in lower RMD for both growth and yield in maize (Tables 4 and 5).

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Table 5. Pearson correlation between AMF root colonisation on RMD of maize growth and yield.

AMF Root Colonisation (%)	RMD of Maize Growth (%)	RMD of Maize Yield (%)
	0.701 **	0.673 **

** significantly different at $p \leq 0.01$.

3.6. Effects of AMF Inoculation and Fertiliser Rate on Photosynthetic Physiological Parameters and Plant NPK Nutrient Uptake in Maize Shoots

Considering the interactive effect, it was evident that AMF inoculation and the fertiliser rate had a statistically significant impact on maize's photosynthetic physiology and plant NPK nutrient content. In the Korat soil series, AMF inoculation significantly improved the leaf chlorophyll content (SPAD), net photosynthetic rate, stomatal conductance, and total shoot NK content across all CF levels. There was no impact on the transpiration rate. Likewise, AMF inoculation increased total shoot P content compared to the non-AMF inoculation at only a 50% CF rate. However, the total shoot NPK content of AMF maize with 50% CF did not significantly differ compared to maize with 100% CF (Table 6(a)). In the Mabbon soil series, AMF similarly increased the leaf chlorophyll content (SPAD), net photosynthetic rate, and total shoot NK content across all CF rates. However, there was no impact on the transpiration rate and stomatal conductance. An interaction between fertiliser rate and AMF inoculation was also observed for total shoot P content. AMF inoculation increased the total shoot P content compared to the non-AMF inoculation at 50% CF and 100% CF. Beyond expectations, the total shoot P content of AMF maize with 50% CF was significantly higher than that of maize grown with 100% CF (Table 6(b)). Lastly, in the Pakthongchai soil series, AMF significantly increased the leaf chlorophyll content (SPAD), transpiration rate, and total shoot PK content across all fertiliser (CF) treatments. However, AMF inoculation significantly increased the net photosynthetic rate and stomatal conductance only at 50% and 100% CF. Similarly, AMF inoculation significantly increased total shoot N content only at 0% and 100% CF. Exceeding assumptions, the total shoot P content of AMF maize with 50% CF was significantly higher than that of maize grown with 100% CF (Table 6(c)).

Table 6. Effect of AMF application and fertiliser rate on photosynthetic physiology of maize at 60 DAP and plant nutrient content of maize shoot at harvesting.

Treatment		Photosynthetic Physiological Parameter				Plant Nutrient Content (g plant^{-1})		
Fertiliser	**AMF**	**SPAD**	**Pn**	**Tr**	**Gs**	**Total N**	**Total P**	**Total K**
				(a) Korat soil				
0% CF	**Non-AMF**	24.55 ^{d}	23.46 ^{d}	5.07	0.256 ^{e}	0.258 ^{e}	0.021 ^{d}	0.303 ^{e}
	AMF	30.31 ^{c}	29.23 ^{c}	5.51	0.312 ^{d}	0.312 ^{d}	0.027 ^{cd}	0.425 ^{d}
50% CF	**Non-AMF**	30.91 ^{c}	29.28 ^{c}	6.05	0.328 ^{c}	0.493 ^{c}	0.035 ^{bc}	0.639 ^{c}
	AMF	35.42 ^{b}	33.22 ^{b}	7.02	0.355 ^{bc}	0.587 ^{b}	0.045 ^{a}	0.767 ^{b}
100% CF	**Non-AMF**	35.78 ^{b}	35.27 ^{b}	7.22	0.370 ^{b}	0.648 ^{b}	0.040 ^{ab}	0.764 ^{b}
	AMF	39.01 ^{a}	38.67 ^{a}	7.40	0.410 ^{a}	0.748 ^{a}	0.047 ^{a}	0.876 ^{a}
				F test				
Fertiliser		**	**	**	**	**	**	**
AMF		**	**	**	*	**	*	**
Fertiliser x AMF		**	*	ns	*	**	*	**
				(b) Mabbon soil				
0% CF	**Non-AMF**	24.64 ^{c}	20.53 ^{d}	5.09	0.291	0.233 ^{f}	0.021 ^{c}	0.286 ^{e}
	AMF	31.70 ^{b}	25.76 ^{c}	5.34	0.322	0.310 ^{e}	0.025 ^{c}	0.379 ^{d}
50% CF	**Non-AMF**	30.65 ^{b}	26.73 ^{c}	5.90	0.363	0.482 ^{d}	0.039 ^{b}	0.649 ^{c}
	AMF	35.40 ^{a}	30.41 ^{b}	6.80	0.375	0.581 ^{bc}	0.051 ^{a}	0.780 ^{b}
100% CF	**Non-AMF**	32.34 ^{b}	29.57 ^{bc}	7.01	0.372	0.643 ^{b}	0.042 ^{b}	0.756 ^{b}
	AMF	37.26 ^{a}	35.95 ^{a}	7.68	0.419	0.732 ^{a}	0.054 ^{a}	0.879 ^{a}
				F test				
Fertiliser		**	**	**	**	**	**	**
AMF		**	*	**	**	**	*	**

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Fertiliser x AMF		**	*	ns	ns	**	*	**
				(c) Pakthongchai soil				
0% CF	**Non-AMF**	25.63 ^{e}	22.48 ^{d}	5.12 ^{d}	0.311 ^{d}	0.266 ^{e}	0.024 ^{c}	0.318 ^{e}
	AMF	28.98 ^{d}	25.13 ^{cd}	5.58 ^{c}	0.325 ^{d}	0.351 ^{d}	0.034 ^{b}	0.430 ^{d}
50% CF	**Non-AMF**	31.31 ^{c}	28.25 ^{c}	5.49 ^{cd}	0.377 ^{c}	0.478 ^{c}	0.034 ^{b}	0.643 ^{c}
	AMF	35.61 ^{b}	32.21 ^{b}	6.87 ^{b}	0.415 ^{b}	0.573 ^{bc}	0.047 ^{a}	0.746 ^{b}
100% CF	**Non-AMF**	34.78 ^{b}	33.17 ^{b}	6.59 ^{b}	0.384 ^{c}	0.620 ^{b}	0.039 ^{b}	0.755 ^{b}
	AMF	39.11 ^{a}	38.18 ^{a}	8.00 ^{a}	0.442 ^{a}	0.780 ^{a}	0.049 ^{a}	0.933 ^{a}
				F test				
Fertiliser		**	**	**	**	**	**	**
AMF		**	*	**	*	**	**	**
Fertiliser x AMF		**	**	*	*	**	**	**

Refer to Table 2 for the meaning of the abbreviations. Pn = net photosynthetic rate (μmol $m^{-2}s^{-1}$); Tr = transpiration rate (mmol $m^{-2}s^{-1}$); Gs = stomatal conductance (mol $m^{-2}s^{-1}$). Means with different letters in a column are significantly different at $p \leq 0.05$ by DMRT. ns = not significantly different; * = significantly different at $p \leq 0.05$; ** = significantly different at $p \leq 0.01$.

4. Discussion

According to the study results, AMF-inoculated maize exhibited greater growth and yield than non-AMF-inoculated maize, with average RMDs of 18.61% and 31.35% for growth and yield, respectively, across all three Ultisol soil series. This is likely because AMF played a crucial role in enhancing plant nutrient uptake in the maize growing in the nutrient-limited Ultisols. Acting as a conduit, AMF facilitate the transfer of nutrients from soil and fertilisers to plants through a symbiotic relationship. The external hyphae of AMF, which are much finer than plant roots, extensively penetrate the soil and access tiny soil pores that plant roots alone cannot reach, effectively expanding the nutrient absorption zone both within and beyond the root zone [35]. Plants colonised by AMF benefit from two nutrient acquisition systems: direct root uptake and AMF-mediated uptake, leading to improved growth compared to non-mycorrhizal plants [5]. Moreover, enhanced N, P, and K contents and improved photosynthetic rates were observed in the AMF-inoculated maize, supporting the conclusions of previous studies. This is due to AMF-improved plant stomatal conductance, which increases the entry of CO_2 into plant leaf tissues, resulting in improved photosynthetic efficiency [36,37]. For instance, Fasusi et al. [38] found that AMF significantly promoted maize vegetative growth by increasing the leaf number, leaf area, leaf length, stem diameter, and plant height. Similarly, Romero-Munar et al. [39] reported that AMF enhanced photosynthetic activity, resulting in increased dry biomass of shoots and roots. Le Pioufle et al. [40] also confirmed positive interactions between AMF colonisation and nutrient content, contributing to better plant growth. Therefore, it is clear that applying AMF in maize cultivation in Ultisols helps overcome the soil fertility limitations associated with this soil type.

The application of AMF enhances the efficiency of chemical fertiliser use. This study found that the use of chemical fertilisers positively influenced both maize growth and yield. However, inoculating maize with AMF in combination with chemical fertiliser significantly improved both growth and yield compared to using chemical fertiliser alone. Previous research also confirmed that AMF can enhance the efficiency of fertilisers. For example, Agbodjato et al. [13] tested maize cultivation in sterilised soil and found that inoculation with AMF from the families Acaulosporaceae and Glomeraceae, combined with chemical fertilisers, significantly promoted maize growth during the vegetative stage, both above ground and in the roots, compared to chemical fertilisers alone. Moreover, their study indicated that AMF inoculation significantly reduced the amount of chemical fertiliser required. Similarly, Sharma et al. [41] evaluated the effects of AMF in sterilised soil. The results showed that AMF inoculation combined with chemical fertiliser significantly increased plant growth, yield, and nutritional quality compared to using chemical fertiliser alone. This effect is attributed to the role of AMF in facilitating nutrient absorption from both the fertiliser and soil,

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thereby improving the plant's nutrient uptake beyond what can be achieved by the root system alone [42].

AMF inoculation also reduced chemical fertiliser usage because AMF supply NPK nutrients to maize [43,44]. The findings indicate that the NPK shoot content in the AMF maize receiving 50% CF was comparable to that of non-AMF maize with 100% CF. In certain instances, the nutrient content of AMF maize with 50% CF was significantly greater than that of non-AMF maize with 100% CF, particularly in terms of phosphorus. In many studies, AMF inoculation, especially when combined with reduced NPK fertilisation, has led to significantly higher maize yields and improved nutrient content in plant tissues [17,45–48]. This mutualistic interaction between AMF and the plant reduces chemical fertiliser use while maintaining or enhancing maize production, thereby promoting sustainable farming practices.

The AMF *Glomus* sp. KUSoil5 demonstrated robust synergy with the maize, resulting in significantly enhanced growth and yield compared to conditions without the AMF. These results underscore the crucial contribution of AMF to maize development and productivity in Ultisols. This is further substantiated by the favourable RMD values and average colonisation rate of 67.48% in maize roots observed across all tested soil series at 0% CF. Research conducted by Nafady et al. [49] indicated that a strong association with AMF correlates positively with better nutrient uptake and enhanced growth and yield in plants. The results of previous experiments are consistent with those of this study, which found that AMF root colonisation had a strong correlation with the RMD of maize growth and yield. This suggests that the extent of AMF colonisation in plant roots reflects the robustness of the symbiotic relationship and the level of nutrient exchange between the host plant and the fungi [5]. These findings demonstrate that AMF form a strong mutualistic relationship with maize, facilitating efficient nutrient exchange between the fungi and the host plant. As a result, AMF can enhance nutrient uptake even in soils with low nutrient availability or without fertiliser application, leading to improved plant growth and yield.

However, the rate of chemical fertiliser application affects the efficiency of AMF. The RMD of maize growth and yield was decreased by 100% CF, resulting in a decline in its benefits for the plants. The effectiveness of the AMF in promoting maize growth and yield decreased as the chemical fertiliser rate increased. Studies by Feng et al. [50] and Kahiluoto et al. [51] have shown that fertiliser application can negatively impact AMF by inhibiting their growth, development, and function. Higher fertiliser rates boost nutrient availability in the soil, which in turn diminishes the signals that plants need to establish mycorrhizal symbiosis [52]. In another sense, when plants can effectively take up sufficient nutrients from fertilisers, they become less reliant on their association with AMF [53]. Using AMF in combination with high levels of chemical fertilisers can potentially hinder plant growth by fostering a parasitic relationship. In these situations, the AMF may continue to extract carbohydrates from the plant without delivering the expected nutrient benefits in return [54]. Therefore, the efficiency of AMF in promoting maize growth and yield declines with increasing chemical fertiliser application rates [55].

AMF root colonisation was also reduced with an increasing chemical fertiliser application rate. Less AMF root colonisation was observed at the recommended 100% CF rate, which resulted in a 43% reduction in root colonisation compared to 0% CF. It is increasingly recognised that high rates of chemical fertiliser use have harmed AMF symbionts, leading to declines in their abundance in agroecosystems [5]. Studies by Zhang et al. [56] and Mandou et al. [57] confirmed that increasing soil nutrient availability by applying high doses of chemical fertilisation significantly decreased AMF root colonisation. This is because the plant reduces the allocation of photosynthetic products to AMF, resulting in a lower degree of AMF colonisation [58,59].

The pH of Ultisols also affects the colonisation maize roots by AMF. According to a study by Fasusi et al. [34], AMF colonisation rates were higher in maize roots grown in sterilised soil with pH 7.2, achieving 86% colonisation. Similarly, Le Pioufle et al. [36] reported 97% colonisation in maize roots grown in a substrate medium. These findings contrast with the results of the present study, where the AMF exhibited average colonisation rates of approximately 67.27%, 65.30%, and 69.46% in

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maize roots growing in the Korat, Mabbon, and Pakthongchai soil series, respectively. This is likely due to highly acidic soils significantly affecting AMF colonisation, reducing AMF spore proliferation and symbiosis [60–62]. The Ultisols used in this study were highly weathered, resulting in soil acidification (pH 5.0–6.0). This acidity likely contributed to the lower AMF colonisation rates of maize roots observed in this study. Therefore, it is recommended that lime be applied to adjust the pH of Ultisols appropriately, thereby improving AMF colonisation and overall soil health.

5. Conclusions

The application of chemical fertilisers in Ultisols, which have low fertility, is crucial as it boosts soil productivity. Nonetheless, the integration of AMF with chemical fertilisers can offer additional benefits for maize growth and yield in this type of soil. This study's findings revealed that AMF inoculation significantly improved the growth and yield of maize compared to chemical fertilisation alone. However, the effectiveness of the AMF inoculation was influenced by the rate of chemical fertiliser applied, with performance decreasing as fertiliser rates increased. Even so, the combination of AMF and fertiliser still led to notable improvements in maize growth and yield compared to use of the recommended rate of fertiliser only. Consequently, inoculating with AMF proves advantageous for maize cultivation in Ultisols. However, future research is required, in which AMF species that demonstrate resilience to high chemical fertiliser rates should be investigated to determine and mitigate the effects of organic fertiliser on AMF efficiency in Ultisols.

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