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Soil microbial population as affected by tillage and rice cultivation modes in *Stagnic Anthrosols* and *Lateritic Red Earth* soils in Southern China

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The microbial population (MP) is considered to be a relatively important part of soil health, quality, and productivity. Therefore, this study aimed to access the effects of tillage and rice cultivation modes on soil MP in *Stagnic Anthrosols* and *Lateritic Red Earth* soils. The treatments were as follows: (i) MDS: land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine of four to six seeds per hill at a planting space of 25 × 15 cm, (ii) RDS: land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine of four to six seeds per hill at a planting space of 25 × 15 cm, (iii) MMT: land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine at a transplanting hill of four to six seedlings and at a transplanting space of 25 × 15 cm, and (iv) RMT: land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine at a transplanting hill of four to six seedlings and a transplanting space of 25 × 15 cm. The findings showed that MDS improved the MP and increases rice yield. MDS showed a high increase in MP in both locations and the rice productivity of 32.81% (1H; first harvest) and 13.91% (2H; second harvest) and 16.48% (1H) and 18.13% (2H) for Zeng-Cheng and Yi-Yang, respectively. In conclusion, MDS was found to be better in improving the MP and increasing rice yield and could be adopted as a suitable approach for improving soil health, quality, and productivity.

KEYWORDS
microbial population, direct seeding, rice cultivation modes, pregerminated seeds, soil health and quality

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Introduction

Soil microbes are vital for the development of soil fertility, maintenance of food security, and mitigation of climate change. As the living portion of soil organic matter, soil microbes play an important role in the function of ecosystems through their complex interactions with the environment (1, 2). These functions include organic matter decomposition and nutrient cycling, including carbon (C) and nitrogen (N) cycling (2–4), and soil aggregate formation and maintenance (5). Furthermore, the microbial population (MP) size and diversity in agricultural soils can be affected by soil management practices. Agricultural land management is one of the most significant anthropogenic activities that alter the soil characteristics, including physical, chemical, and biological property processes. Previous studies have shown that microbial biomass can be altered by changes in agricultural management practices (6–15). Microbial indicators such as enzyme activities are good potential indices of soil quality and health because of their role in soil biological and biochemical processes, ease of measurement, and rapid response to changes in soil quality induced by the management (14). Appropriate tillage combined with the right cultivation mode of rice on paddled fields can have a thorough impact on the soil MP and rice yield, as an improvement in rice yield is a result of the enhancement of soil microbes and also reduces the strenuous ways of seedling transplanting in paddy fields. The aim of the present study was to investigate the effects of different tillage and rice cultivation modes on soil MP (bacteria, fungi, actinomycete, catalase, urease, and phosphatase) and on rice yield.

Materials and methods

An experiment was established at Zeng-Cheng in Guangdong Province of Southern China (23°13′ N, 113°81′ E, altitude 11 m, Figure 1A) and Yi-Yang in Hunan Province of Southern China (29°07′40″ N, 112°25′25″ E, 27 m in altitude, Figure 1B) for two seasons (2017 and 2018). The meteorological data of the crop seasons are given in Table 1. The soil under experimentation was sandy-loam and sandy-clay-loam for Zeng-Cheng and Yi-Yang, respectively. The soils of the study sites are classified as *Stagnic Anthrosols* for Zeng-Cheng and *Lateritic Red Earth* for Yi-Yang, which developed from the Quaternary Red Earth (16). The Zeng-Cheng site had N, P, and K content of 39.52, 13.32, and 31.19 kg ha^{-1}, respectively, with a pH value of 5.65, and Yi-Yang had soil N, P, and K content of 100, 8.5, and 112 kg ha^{-1}, respectively, with a pH value of 6.5. The pre-soil condition of the experimental sites is given in Table 2. Soil bacteria, fungi, and actinomycetes were determined by the plate inoculation method (17). Soil urease was determined by the automated calorimetric method (17). Soil catalase was determined by the volumetric method (17). Soil phosphatase was determined by the phenyl phosphate sodium colorimetric method (17).

Four cultivation modes, viz., (i) MDS: land tilled twice with a moldboard plow (at 30 cm depth) and hill-seeding of pregerminated seeds with a direct seeding machine of four to six seeds per hill at a planting space of 25 × 15 cm, (ii) RDS: land tilled twice with a rotary tiller (at 30-cm depth) and hill-seeding of pregerminated seeds with a direct seeding machine of four to six seeds per hill at a planting space of 25 × 15 cm, (iii) MMT: land tilled twice with a moldboard plow (at 30-cm depth) and 15-day-old seedlings were mechanically transplanted with a transplanting machine at a transplanting hill of four to six seedlings and at a transplanting space of 25 × 15 cm, and (iv) RMT: land tilled twice with a rotary tiller (at 30-cm depth) and 15-day-old seedlings were mechanically transplanted with a transplanting machine at a transplanting hill of four to six seedlings and a transplanting space of 25 × 15 cm. The experimental field measured 10,990 m^2, with subdivided plots:

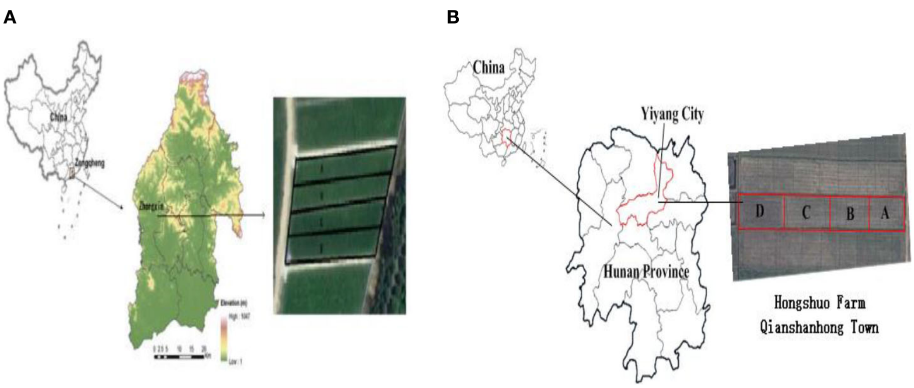

FIGURE 1
Site location of South China Agricultural University Research Station: **(A)** Zhongxi Town, Zeng-Cheng District, Guangzhou City, Guangdong Province, China, and **(B)** Yi-Yang City, Hunan Province, China.

TABLE 1 Mean meteorological data for crop growth season during 2017 and 2018.

Climatic condition	Zeng-Cheng	Yi-Yang
Precipitation (mm)	2,709.15	1,526.94
Wind speed (m/s)	24.05	22.94
Temperature (°C)	22.05	18.45
Relative humidity (%)	721.05	918.44
Sunshine hours (h)	1,665.35	1,491.05

MDS and RDS (100 m × 35 m) and MMT and RMT (57 m × 35). Aromatic rice cultivar *Meixiangzhan-2 and Huanghuazha*, respectively, for Zeng-Cheng and Yi-Yang, with a maturity period between 111 and 114 days, were sown through direct hill drop method by 2BDCSP Precision Rice Hill-Drop Drilling Machine and transplanted by YANMAR VP7D25 Rice Transplanter. The first harvest (H1) was done in August 25 and August 18, respectively, in 2017 and 2018, and the second harvest (H2) was done in October 20 in 2017 and 2018 at both locations.

Grain yield measurement

Rice grains were harvested at maturity from three-unit sampling areas (1.00 m^2) randomly selected in each plot and then machine-threshed at both farm sites. The harvested grains were sun-dried at 13.5% moisture content and weighted in order to determine the grain yield. FUQIANG 4LZ-427 Full-Fill Grain Combine Harvester was used to harvest the whole rice fields.

Statistical analysis

Statistical analysis was conducted using IBM SPSS software 23.0 (SPSS Inc., Chicago, IL, USA). Duncan's multiple range test at 5% probability was performed to compare the means of different treatments.

Results

Culturable bacteria population

Culturable bacteria at 0–30-cm depth were highest under MDS (2.55 × 10^5 cfu·g^{-1} dry soil), followed by RDS (2.40 × 10^5 cfu·g^{-1} dry soil), MMT (2.22 × 10^5 cfu·g^{-1} dry soil), and RMT (1.88 × 10^5 cfu·g^{-1} dry soil) during 1H and MDS (2.77 × 10^5 cfu·g^{-1} dry soil), followed by RDS (2.57 × 10^5 cfu·g^{-1} dry soil), MMT (2.37 × 10^5 cfu·g^{-1} dry soil), and RMT (1.79 × 10^5 cfu·g^{-1} dry soil) during 2H for Zheng-Cheng as shown in Figure 2. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS (2.85 × 10^5 cfu·g^{-1} dry soil), followed by RDS (2.65 × 10^5 cfu·g^{-1} dry soil), MMT (2.34 × 10^5 cfu·g^{-1} dry soil), and RMT (1.82 × 10^5 cfu·g^{-1} dry soil) during 1H and MDS (2.08 × 10^5 cfu·g^{-1} dry soil), followed by RDS (1.73 × 10^5 cfu·g^{-1} dry soil), RMT (1.27 × 10^5 cfu·g^{-1} dry soil), and MMT (0.71 × 10^5 cfu·g^{-1} dry soil) during 2H for Yi-Yang as shown in Figure 2.

Culturable fungi population

The soil culturable fungi (at 0–30-cm depth) under tillage and different cultivation modes were highest under MDS (1.64 × 10^3 cfu·g^{-1} dry soil), followed by RDS (1.47 × 10^3 cfu·g^{-1} dry soil), MMT (1.42 × 10^3 cfu·g^{-1} dry soil), and RMT (1.34 × 10^3 cfu·g^{-1} dry soil) during 1H and MDS (1.76 × 10^3 cfu·g^{-1} dry soil), followed by MMT (1.47 × 10^3 cfu·g^{-1} dry soil), RMT (1.40 × 10^3 cfu·g^{-1} dry soil), and RDS (1.26 × 10^3 cfu·g^{-1} dry soil) during 2H for Zheng-Cheng as shown in Figure 3. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS (0.24 × 10^3 cfu·g^{-1} dry soil), followed by RDS (0.19 × 10^3 cfu·g^{-1} dry soil), MMT (0.10 × 10^3 cfu·g^{-1} dry soil), and RMT (0.09 × 10^3 cfu·g^{-1}

TABLE 2 Basic soil properties at 0–30 cm of soil depth before the experiment.

Soil properties	Yi-Yang	Zeng-Cheng
Sand (%)	57	65
Silt (%)	9	27
Clay (%)	34	8
Soil texture classes	Sandy-clay-loam	Sandy-loam
Climate	Subtropical Monsoon	Subtropical Monsoon
Soil type	Stagnic Anthrosols	Lateritic Red Earth
Bacteria (×10 cfu·g^{-1} dry soil)	2.79	2.21
Fungi (×10^3 cfu·g^{-1} dry soil)	0.08	1.21
Actinomycetes (×10^4 cfu·g^{-1} dry soil)	5.41	2.80
Catalase [0.1 N $KMnO_4$ (ml·g^{-1})]	43.39	1.61
Phosphatase [P_2O_5 (mg·kg^{-1})]	159.66	69.03
Urease [NH_4^+ – N (mg·kg^{-1})]	1,211.50	47.50

dry soil) during 1H and MDS (0.24 × 10^3 cfu·g^{-1} dry soil), followed by RDS (0.16 × 10^3 cfu·g^{-1} dry soil) and MMT and RMT (0.11 × 10^3 cfu·g^{-1} dry soil) during 2H for Yi-Yang as shown in Figure 3.

Culturable actinomycete population

Culturable actinomycete populations at 0–30-cm depth were highest under MDS (3.19 × 10^4 cfu·g^{-1} dry soil), followed by RMT (3.16 × 10^4 cfu·g^{-1} dry soil), RDS (2.99 × 10^4 cfu·g^{-1} dry soil), and MMT (2.89 × 10^4 cfu·g^{-1} dry soil) during 1H and MDS (3.33 × 10^4 cfu·g^{-1} dry soil), followed by RDS (3.12 × 10^4 cfu·g^{-1} dry soil), MMT (3.04 × 10^4 cfu·g^{-1} dry soil), and RMT (2.98 × 10^4 cfu·g^{-1} dry soil) during 2H for Zheng-Cheng as shown in Figure 4. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS (5.04 × 10^4 cfu·g^{-1} dry soil), followed by RDS (3.71 × 10^4 cfu·g^{-1} dry soil), RMT (2.77 × 10^4 cfu·g^{-1} dry soil), and MMT (2.24 × 10^4 cfu·g^{-1} dry soil) during 1H and MDS (5.72 × 10^4 cfu·g^{-1} dry soil), followed by RDS (5.30 × 10^4 cfu·g^{-1} dry soil) and MMT (4.62 × 10^4 cfu·g^{-1} dry soil) and RMT (4.42 × 10^4 cfu·g^{-1} dry soil) during 2H for Yi-Yang as shown in Figure 4.

Catalase activity

Catalase activity at 0–30-cm depth was highest under MDS [1.72 (0.1 N $KMnO_4$, ml·g^{-1})], followed by RDS [1.60 (0.1 N $KMnO_4$, ml·g^{-1})], RMT [1.36 (0.1 N $KMnO_4$, ml·g^{-1})], and MMT [1.07 (0.1 N $KMnO_4$, ml·g^{-1})]) during 1H and MDS [1.71 (0.1 N $KMnO_4$, ml·g^{-1})], followed by RDS [1.60 (0.1 N $KMnO_4$, ml·g^{-1})], MMT [1.53 (0.1 N $KMnO_4$, ml·g^{-1})], and RMT [1.46 [(0.1 N $KMnO_4$, ml·g^{-1})] during 2H for Zheng-Cheng as shown in Table 3. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS [45.85 (0.1 N $KMnO_4$, ml·g^{-1})], followed by RDS [44.39 (0.1 N $KMnO_4$, ml·g^{-1})], MMT [42.01 (0.1 N $KMnO_4$, ml·g^{-1})], and RMT [40.44 (0.1 N $KMnO_4$, ml·g^{-1})] during 1H and MDS [25.56 (0.1 N $KMnO_4$, ml·g^{-1})], followed by RDS [24.72 (0.1 N $KMnO_4$, ml·g^{-1})], MMT [22.55 (0.1 N $KMnO_4$, ml·g^{-1})], and RMT [21.66 (0.1 N $KMnO_4$, ml·g^{-1})] during 2H for Yi-Yang as shown in Table 3.

Phosphatase activity

The activity of phosphatase at 0–30-cm depth was highest under MDS [73.26 (P_2O_5, mg·kg^{-1})], followed by RDS [69.34 (P_2O_5, mg·kg^{-1})], MMT [66.34 (P_2O_5, mg·kg^{-1})], and RMT [64.59 (P_2O_5, mg·kg^{-1})] during 1H and MDS [79.52 (P_2O_5, mg·kg^{-1})], followed by RDS [75.41 (P_2O_5, mg·kg^{-1})], MMT [73.05 (P_2O_5, mg·kg^{-1})], and RMT [70.02 (P_2O_5, mg·kg^{-1})] during 2H for Zheng-Cheng as shown in Table 3. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS [224.71 (P_2O_5, mg·kg^{-1})], followed by RDS [221.18 (P_2O_5, mg·kg^{-1})], MMT [218.26 (P_2O_5, mg·kg^{-1})], and RMT [216.95 (P_2O_5, mg·kg^{-1})] during 1H and MDS [145.64 (P_2O_5,

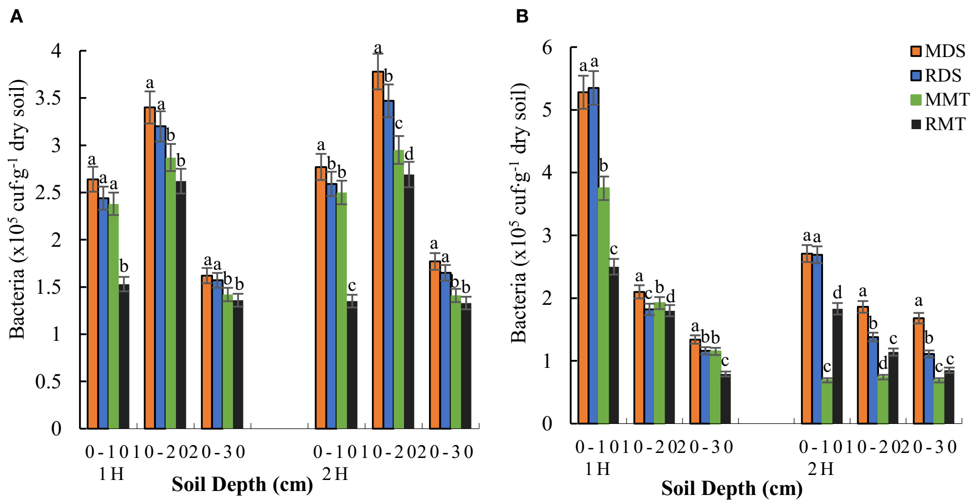

FIGURE 2
Tillage and rice cultivation modes on culturable bacteria population: **(A)** Zeng-Cheng and **(B)** Yi-Yang. MDS, land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine; RDS, land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine; MMT, land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine; RMT, land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine. Figures in the column with common letter(s) do not differ significantly at the 5% level of Duncan's multiple range text. 1H, first harvest; 2H, second harvest.

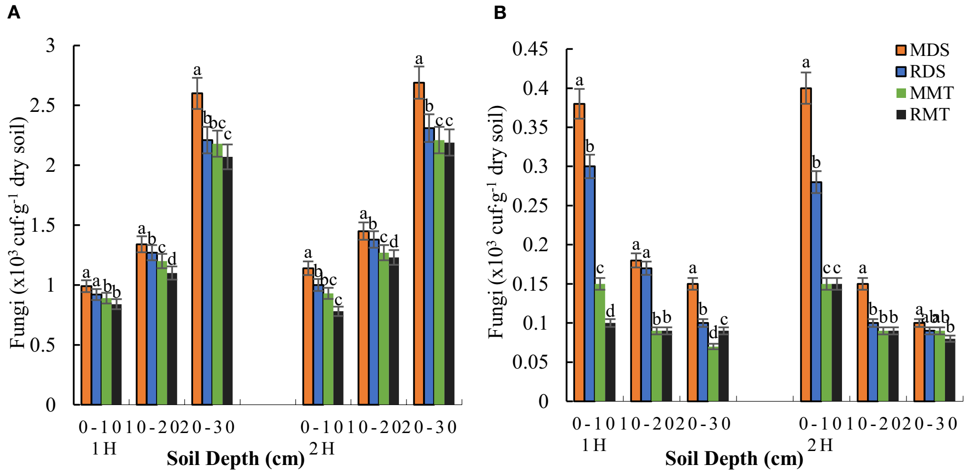

FIGURE 3
Tillage and rice cultivation modes on culturable fungi population: **(A)** Zeng-Cheng and **(B)** Yi-Yang. MDS, land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine; RDS, land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine; MMT, land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine; RMT, land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine. Figures in the column with common letter(s) do not differ significantly at the 5% level of Duncan's multiple range text. 1H, first harvest; 2H, second harvest.

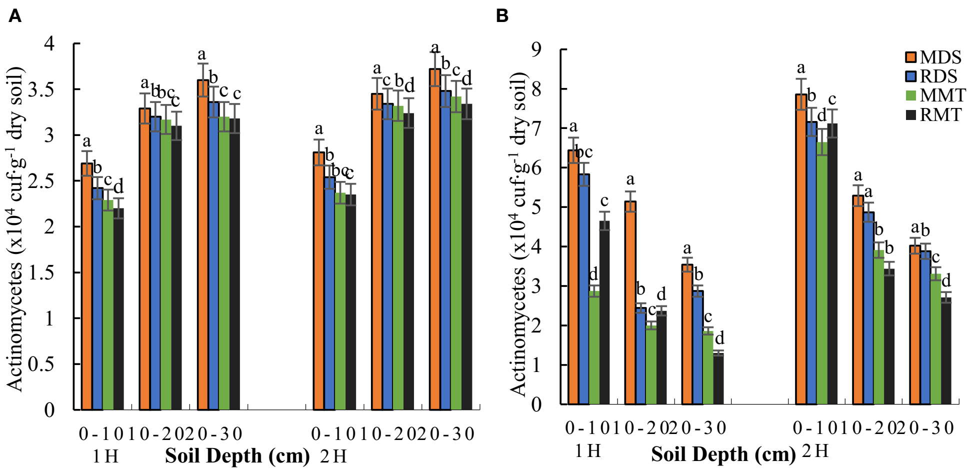

FIGURE 4
Tillage and rice cultivation modes on culturable actinomycetes population: **(A)** Zeng-Cheng and **(B)** Yi-Yang. MDS, land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine; RDS, land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine; MMT, land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine; RMT, land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine. Figures in the column with common letter(s) do not differ significantly at the 5% level of Duncan's multiple range text. 1H, first harvest; 2H, second harvest.

mg·kg^{-1})], followed by RDS [132.93 (P_2O_5, mg·kg^{-1})], and RMT [117.79 (P_2O_5, mg·kg^{-1})], and MMT [116.68 (P_2O_5, mg·kg^{-1})] during 2H for Yi-Yang as shown in Table 3.

Urease activity

The soil urease activity (at 0–30-cm depth) under tillage and different cultivation modes was highest under MDS [49.34 (NH_4^+ – N, mg·kg^{-1})], followed by RDS [48.07 (NH_4^+ – N, mg·kg^{-1})], MMT [47.38 (NH_4^+ – N, mg·kg^{-1})], and RMT ([46.03 (NH_4^+ – N, mg·kg^{-1})] during 1H and MDS [50.18 (NH_4^+ – N, mg·kg^{-1})], followed by RDS [48.77 [(NH_4^+ – N, mg·kg^{-1})], MMT [48.05 (NH_4^+ – N, mg·kg^{-1})], and RMT [46.78 (NH_4^+ – N, mg·kg^{-1})] during 2H for Zheng-Cheng as shown in Table 3. Similar trends were recorded for bacteria at 0–30-cm depth, with MDS [642.74 (NH_4^+ – N, mg·kg^{-1})], followed by RDS [587.14 (NH_4^+ – N, mg·kg^{-1})], MMT [562.39 (NH_4^+ – N, mg·kg^{-1})], and RMT [550.68 (NH_4^+ – N, mg·kg^{-1})] during 1H and MDS [1,107.87 (NH_4^+ – N, mg·kg^{-1})], followed by RDS [1,040.43 (NH_4^+ – N, mg·kg^{-1})], and MMT [966.39 (NH_4^+ – N, mg·kg^{-1})], and RMT [912.22 (NH_4^+ – N, mg·kg^{-1})] during 2H for Yi-Yang as shown in Table 3.

Rice grain yield

As shown in Table 4, different tillage and rice cultivation modes affected the rice grain yield significantly. The highest grain yield was recorded under MDS. However, there was a significant increase of 32.81 and 13.91% in Zeng-Cheng and

TABLE 3 Catalase, phosphatase, and urease activity as affected by tillage and rice cultivation modes.

Soil depth	Treatment	Catalase [0.1NKMnO$_4$ (ml·g^{-1})]		Phosphatase [P_2O_5 (mg·kg^{-1})]		Urease [NH_4^+ – N (mg·kg^{-1})]	
		1H	2H	1H	2H	1H	2H
Zeng-Cheng							
	MDS	1.71a	1.76a	88.43a	95.12a	55.89a	56.63a
0–10 cm	RDS	1.58ab	1.56ab	82.91a	92.11a	54.45b	55.38ab
	MMT	1.37b	1.46b	79.26a	90.56a	53.92b	54.64b
	RMT	1.34b	1.45b	77.68a	86.42a	51.46c	52.31c
	MDS	1.88a	1.90a	74.44a	78.72a	47.51a	48.73a
10–20 cm	RDS	1.78b	1.85a	71.10ab	73.15a	45.84ab	46.64ab
	MMT	1.58c	1.82a	66.88b	68.96a	44.94b	45.66b
	RMT	1.44c	1.72a	65.09b	67.55a	44.23b	44.72b
	MDS	1.58a	1.48a	56.90a	64.72a	44.62a	45.17a
20–30 cm	RDS	1.45a	1.40a	54.02b	60.96a	43.28a	44.30ab
	MMT	1.34a	1.30a	52.88c	59.62a	43.28a	43.85b
	RMT	1.29a	1.22a	50.99d	56.09a	42.56a	43.19b
Yi-Yang							
	MDS	52.33a	27.24a	224.70a	205.20a	1,024.09a	1,559.34a
0–10 cm	RDS	50.86b	26.61a	223.50ab	198.30b	1,014.95b	1,544.3b
	MMT	47.42c	22.84c	217.97c	172.96d	877.57c	1,447.5c
	RMT	45.43d	24.65b	221.50b	178.30c	861.07c	1,243.06d
	MDS	47.63a	26.69a	225.70a	144.80a	618.68a	1,157.79a
10–20 cm	RDS	44.89ab	25.00c	218.50b	122.10b	619.35a	989.21b
	MMT	43.12b	23.01b	215.84b	116.59c	518.7b	927.5d
	RMT	39.13c	20.66d	218.00b	110.60d	473.21c	978.94c
	MDS	37.58a	22.77a	223.70a	86.95a	352.88a	606.48a
20–30 cm	RDS	37.41a	22.55a	221.60b	78.40b	294.59b	587.79b
	MMT	35.50b	21.79b	221.14b	60.49d	264.49c	524.20c
	RMT	36.75a	19.66c	211.50c	64.47c	109.24d	514.65d

Figures in the column with common letter(s) do not differ significantly at the 5% level of Duncan's multiple range text.
MDS, land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine; RDS, land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine; MMT, land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine; RMT, land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine; 1H, first harvest; 2H, second harvest.

TABLE 4 Tillage and rice cultivation modes on grain yield.

Treatment	Grain yield (t·ha^{-2})			
	Zeng-Cheng		Yi-Yang	
	1H	2H	1H	2H
MDS	7.65	3.93	8.13	4.04
RDS	7.24	3.77	7.68	3.62
MMT	6.73	3.53	7.17	3.56
RMT	5.76	3.45	6.98	3.42

Figures in the column with common letter(s) do not differ significantly at the 5% level of Duncan's multiple range text.
MDS, land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine; RDS, land tilled twice with a rotary tiller and hill-seeding of pregerminated seeds with a direct seeding machine; MMT, land tilled twice with a moldboard plow and 15-day-old seedlings were mechanically transplanted with a transplanting machine; RMT, land tilled twice with a rotary tiller and 15-day-old seedlings were mechanically transplanted with a transplanting machine; 1H, first harvest; 2H, second harvest.

16.48% and 18.13% in Yi-Yang in both harvest times (1H and 2H), respectively, under MDS compared to RMT.

Discussion

MPs were significantly affected by tillage and rice cultivation modes in both locations. Among the different tillage practices, a significantly higher MP was recorded under MDS at the harvest of the rice than the other tillage practices in Zeng-Cheng and Yi-Yang. Culturable bacteria were higher under MDS due to the excessive incorporation of rice stover and the high stockpile. The tillage practice resulted in the accessibility of substrates by improving the profusion of bacteria (18, 19). Possible compaction of the soil, which might have resulted from mechanical transplanting during the cultivation mode, and the likelihood of less stockpile of preceding rice stover under MMT and RMT resulted in a decrease of culturable bacteria population. The fungi population was greater under MDS due to the excessive incorporation of rice stover and the improved soil infiltration resulting from organic matter decomposition from rice stover incorporation. MDS caused less disturbance during the establishment of the rice, leading to an increase in culturable fungi population. The culturable fungi population decreased under MMT and RMT, which might have resulted from compaction as a result of the rice cultivation mode during mechanical transplanting, which is in support of the finding by Asenso etal. (19) who observed reduced fungi count under moldboard plowing and rotary tillage each combined with mechanical transplanting. The culturable actinomycete population was greater under MDS, which may be due to the high accumulation of rice stover on the soil surface, possibly leading to more accumulation of soil organic matter by tending to improved soil aeration and thus resulting to improved actinomycete population. The catalase activity was greater under MDS, which may have resulted from the lesser disturbance of the soil by the tillage practice and at the rice establishment method enhancing the substrates, which is in support of the work of Jin etal. (20), as a greater catalase was observed under shallow tilling practices. There was a greater increase in urease and phosphatase activity under MDS, resulting from the less disturbed soil by the tillage practice and the rice cultivation mode which is in agreement with the findings of Jin etal. (20), and a high accumulation of rice stover, leading to improved putrefaction of organic matter and resulting in improved aeration in the soil as an improvement in MP results in the enhancement of soil enzyme abundance.

Tillage and rice cultivation modes affected the grain yield. The highest rate of grain yield was produced in MDS that was statistically greater than in RMT and MMT for 1H and 2H in both locations. Applying RMT caused a reduction of 1.89 and 0.48 t·h^2 as well as 1.15 and 0.62 t·h^2 for 1H and 2H in Zeng-Cheng and Yi-Yang, respectively. The rice yield was impacted by MDS as it provided favorable soil condition and more soil nutrient availability resulting from less soil uproar and thus enhancing root proliferation for moisture and nutrient absorption, which is confirmed by Ali etal. (21) and Asenso etal. (19) who observed a higher grain yield of rice under direct seeding compared with swamped rice transplanting.

Conclusion

In summary, there are significant variations in the impact of tillage practice and rice cultivation modes on MP and rice productivity. MDS was observed with improvement in MP and rice yield. To achieve maximum and sustainable rice production, management methods that ensure the right combined effects of tillage practice and rice cultivation mode should be followed. Our results therefore suggest that improved soil MP and rice yield could be attained by adopting treatment MDS (land tilled twice with a moldboard plow and hill-seeding of pregerminated seeds with a direct seeding machine) and therefore recommended for soil health and quality and sustainable paddy rice production.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Author contributions

Conceptualization and project administration and supervision: JL. Formal analysis and investigation, writing—original draft preparation, and submission: EA. Data processing: ZW. Data processing and analysis: TK. Writing—review and editing and project administration and supervision: LH. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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