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A sustainable approach to improving agrifood production: getting the balance right between organic soil amendments and chemical fertilizers

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Abstract

Purpose – We analyzed the effects of different combinations of organic soil amendments (OSAs) and chemical fertilizers on agrifood production, focusing on banana yields in China, the second-largest producer of bananas globally.
Design/methodology/approach – We computed these combinations by dividing the expenditures on OSAs by those on chemical fertilizers and called them OSA-CF ratios. First, we classified farmers based on quintiles of expenditures on chemical fertilizers. Then, we studied the association between OSA-CF ratios and banana yields for each quintile. We also considered an alternate specification in which farmers were grouped along the OSA-CF ratio continuum. The first group comprised farmers not using OSAs. Their OSA-CF ratio was zero. Farmers applying low, medium, and high OSA-CF ratios constituted groups two, three, and four; the groups were delineated based on the OSA-CF ratio tertiles, and the associations between tertiles of OSA-CF ratios and banana yields for each quintile were analyzed. The data used in this study were collected by surveying 616 households in three major banana-producing provinces (Guangdong, Hainan, and Yunnan) of China. Standard linear regressions and the two-stage predictor substitution method were employed to complete the analysis.
Findings – There were variations in the effects of OSA-CF ratios on banana yields obtained by farmers iifferent quintiles. For the first and second quintiles, low, medium, and high OSA-CF ratios improved banana yields relative to not using OSAs. For farmers in the first quintile using only chemical fertilizers, applying a low OSA-CF ratio was associated with an improvement of 792 kg/mu in banana yields. For their counterparts in the second quintile, the same transition was associated with a gain of 534 kg/mu. For the fifth quintile, comprising farmers spending 320 yuan/mu or more on chemical fertilizers, applying a high OSA-CF ratio instead of using only chemical

JEL Classification — C21, Q24, Q56, Q57

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Corrigendum: It has come to the attention of the publisher that the article "Vatsa, P., Zheng, H. and Ma, W. (2024), "A sustainable approach to improving agrifood production: getting the balance right between organic soil amendments and chemical fertilizers", *China Agricultural Economic Review*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/CAER-08-2023-0208, contains an error in the author's name. This error was introduced during the submission process. Puneet Vasta has now been corrected to Puneet Vatsa. The authors sincerely apologise for this error and any misunderstanding.

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fertilizers was associated with a 401 kg/mu decline in banana yields. Even so, for this group, no differences were observed between the yields of farmers not applying OSAs and those using low and medium OSA-CF ratios.
Practical implications – Banana farmers in southern China, using only chemical fertilizers, can improve yields by combining them with OSAs if their chemical fertilizer expenditures are less than 66.67 yuan/mu. Those using only chemical fertilizers and spending between 68 yuan/mu and 300 yuan/mu on them can maintain yields by applying OSAs in conjunction with chemical fertilizers. However, yields may decline for farmers using only chemical fertilizers and spending 320 yuan/mu or more on them if they incorporate OSAs such that the OSA-CF ratio reaches 0.78 or higher. Overall, combining OSAs with chemical fertilizers can improve yields while attenuating the adverse effects of chemical fertilizers on the environment. Policymakers should inform farmers of these benefits and accelerate the transition to sustainable agriculture through educational and awareness programs.
Originality/value – Farmers apply OSAs such as organic fertilizers and farmyard manure to adjust and remedy soil nutrition to improve farm productivity. However, little is known about how combining OSAs with chemical fertilizers affects banana yields. This study provided the first attempt to explore the associations between OSA-CF ratios and banana yields using cross-sectional data on farming households.

Keywords Agrifood production, Organic soil amendments, Chemical fertilizers, Bananas, China
Paper type Research paper

1. Introduction

First implemented at an industrial scale in 1913, the Haber-Bosch process synthesized ammonia from atmospheric nitrogen and hydrogen, enabling the mass production of nitrogenous fertilizers. The process proved transformative for global food production—almost half of the global population would go hungry without chemical fertilizers. Chemical fertilizers have yielded profound benefits for humanity; however, using them has also been detrimental to environmental and human health. For example, excess nitrogen not utilized by plants can seep into water sources, creating dead zones in water bodies and polluting drinking water; it also contributes to acid rain, air pollution, accumulation of pesticides, and ozone formation at the ground level (EPA, 2021). Chemical fertilizers stifle the activity of nitrogen-fixing bacteria, altering the bacterial composition and depleting soil nutrient density (Montgomery and Biklé, 2021; Yu *et al.*, 2023). Furthermore, recent meta-analyses have shown a positive association between certain forms of cancer and drinking water contamination from chemical fertilizers (Essien *et al.*, 2022; Picetti *et al.*, 2022).

Organic soil amendments (OSAs) such as organic fertilizers and farmyard manure can play an integral role in sustainable agriculture [1]. They can help farmers use on-farm resources, improve crop yields, make farm operations safer, more profitable, and environmentally friendly in the long run, and mitigate the adverse effects of chemical fertilizers on environmental and human health. Evidence shows that OSAs can enhance the fertility and water content of the soil, reduce the carbon and nitrogen footprint of agriculture, increase resistance to plant pathogens, and activate soil bacterial communities (Agegnehu *et al.*, 2016; Bamdad *et al.*, 2022; Hoover *et al.*, 2019; Ma *et al.*, 2018; Tabe-Ojong *et al.*, 2023). Even so, applying OSAs may pose environmental risks such as nitrate pollution (Li *et al.*, 2017). Overall, however, there is a consensus that the adverse effects of chemical fertilizer use on the environment and human health can be alleviated by using OSAs and weaning agriculture from its dependence on chemical fertilizers. Whether and to what extent combining OSAs with chemical fertilizers improves crop yields is undecided. Although the application of OSAs was associated with improved yields of corn and soybean (Hoover *et al.*, 2019), strawberry (Li *et al.*, 2022), wheat (Zheng *et al.*, 2021a), and tobacco (Jiang *et al.*, 2022), the same compromised spinach yields (Zhuang *et al.*, 2019). As for the associations between OSAs and banana yields, Bass *et al.* (2016) found that biochar reduced yields in tropical Australia, whereas Shen *et al.* (2013) reported improvements in yields in China's Hainan province resulting from the application of bio-organic fertilizers.

It is common to study the effects of fertilizers on yields experimentally. In such studies, researchers study soil samples and yields from plots subject to various treatments: the type of fertilizers, their quantities, or both may be varied, and measurements are taken routinely (Bass *et al.*, 2016; Hoover *et al.*, 2019; Jiang *et al.*, 2022; Koch *et al.*, 2018; Shen *et al.*, 2013; Zhai *et al.*, 2022).

Although designed experimental studies may afford researchers significant control over key parameters, their results are derived from specific and often a limited number of scenarios. For example, Hoover *et al.* (2019) used three treatments across two experimental phases to study the effects of poultry manure fertilizers on corn and soybean farms in a long-term experiment, while Zhai *et al.* (2022) used a randomized block design comprising five treatments, each having three replicates. Notwithstanding the utility of these experiments within the context in which they are conducted and the accuracy of the data they generate, it is often challenging, even ill-advised, to generalize the conclusions of experimental studies with a few treatments.

Analyzing how crop yields change along a continuum of treatments widens the lens, providing a more well-rounded view of the associations between yields and the treatments of interest. This approach is especially advantageous as farmers increasingly apply different combinations of OSAs and chemical fertilizers to adjust and remedy soil nutrition. Because different combinations of OSAs and chemical fertilizers are likely to affect yield differently, it is important to understand these effects to inform decisions pertaining to fertilizer use. The principal objective of this paper is to improve this understanding.

This study is novel on two counts. The first is methodological: the effects of a continuum instead of a few combinations of OSAs and chemical fertilizers, i.e. OSA-CF ratios, on banana yields are estimated. The second pertains to the data used in this study. We analyzed data collected from farming households in China's three major banana-producing provinces—Hainan, Yunnan, and Guangdong. These are bespoke, fit-for-purpose data allowing us to provide practical insights into the linkages between fertilizer use and banana yields. OSA-CF ratios are calculated by dividing the expenditures on OSAs by the expenditures on chemical fertilizers. Our approach is as follows. First, we split the sample into quintiles based on how much farmers spend on chemical fertilizers (for details on the expenditures in each quintile, please refer to Table A1 in the Appendix). To be clear, farmers using small amounts of chemical fertilizers may have similar OSA-CF ratios as those applying these fertilizers generously—the latter may apply high quantities of OSAs and chemical fertilizers, whereas the former may use only small amounts of both. Despite their similarities, however, the ratios will likely affect yields differently in the two groups. Therefore, it is critical to account for how much fertilizer is applied to understand the effects of OSA-CF ratios on yield. Second, we consider four groups of farmers along the OSA-CF ratio continuum. The first group comprises farmers not using any OSAs; their OSA-CF ratio is zero. Farmers using low, medium, and high OSA-CF ratios constitute groups two, three, and four; the groups are delineated based on the OSA-CF ratio tertiles. This allows us to examine whether farmers using only chemical fertilizers can improve yields by combining them with OSAs and which combinations generate the highest yields. Last, we estimate linear regressions to examine the associations between OSA-CF ratios and banana yields while controlling for potential confounders for each quintile.

There are three main reasons why studying banana farmers in China are important. First, with an annual output of more than 11 million tonnes, China is the second-largest producer of bananas globally (FAO, 2022). Second, China has the world's largest population of smallholder farmers: 260 million (Song *et al.*, 2021). Third, it is the world's largest consumer of chemical fertilizers, accounting for the highest share of the global excess nitrogen (Ritchie, 2021). Given the scale of production, the number of farmers directly involved, and the severity of environmental degradation due to the over-application of chemical fertilizers, the effects of combining chemical fertilizers with OSAs on banana yields in China warrant attention.

Our results show that for farmers spending less than 66.67 yuan/mu on chemical fertilizers, incorporating OSAs with chemical fertilizers was associated with higher banana yields. Using different combinations of OSAs and chemical fertilizers did not affect yields for farmers using only chemical fertilizers and spending between 68 yuan/mu and 300 yuan/mu. However, for farmers spending over 320 yuan/mu on chemical fertilizers, combining them with OSAs such that the OSA-CF ratio reached or exceeded 0.78 was associated with lower yields.

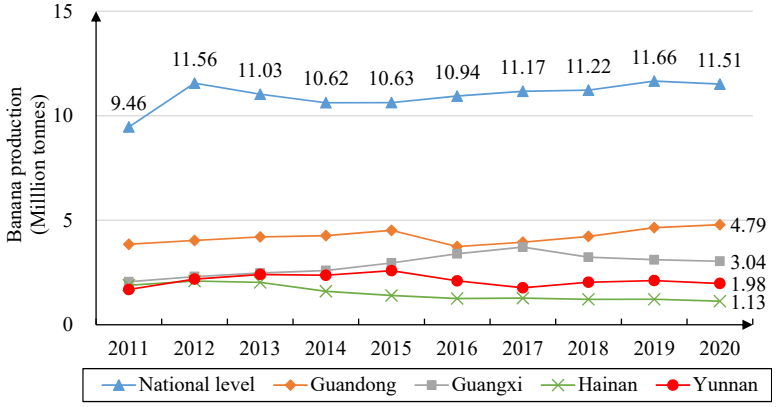
Our analysis is timely and has global implications, given the unprecedented increase in fertilizer prices in 2022. Farmers may accelerate their transition to using OSAs if chemical fertilizer prices remain high. However, such transitions are not and ought not to be abrupt. The failed, ill-advised ban on chemical fertilizer imports in Sri Lanka in 2021 highlighted the perils of a quick switch to organic farming (The Economist, 2021). Moreover, the transition to organic fertilizers may prove especially unsettling for smallholder farmers in developing countries who do not have the wherewithal to purchase expensive inputs and have limited credit access. Thus, analyzing how the trade-off between using OSAs and chemical fertilizers affects these farmers is particularly important.

The remainder of the paper is structured as follows. We provide a brief overview of banana production and fertilizer use in China in Section 2. The method and data are described in Section 3. The empirical results are discussed in Section 4, and Section 5 concludes the study with a summary of the results, policy implications, and avenues for future research.

2. Banana production and fertilizer use in China

Due to favorable climatic conditions for producing bananas in Guangdong, Yunnan, Guangxi, and Hainan, China's banana production is concentrated in these southern provinces. Figure 1 shows that in 2020, the four provinces produced 10.94 million tonnes of bananas, constituting 95% of the national total. China's average annual production of bananas between 2010 and 2017 was 11 million tonnes, making China the second biggest banana producer globally, behind only India (FAO, 2022).

Figure 2 illustrates the annual fertilizer consumption and how much of it is used relative to manure. China used 47.55 million tonnes of chemical fertilizers in 2019; this amounted to a quarter of the global fertilizer consumption. Chemical fertilizer use increased during the first half of the 2010s, peaking at 55.61 tonnes in 2014. During the same time, the amount of manure applied decreased, falling from 5.03 tonnes in 2010 to 4.81 tonnes in 2014. Consequently, the chemical fertilizer to manure ratio declined between 2010 and 2014, reaching as low as 8.64% in 2014. The quantities of chemical fertilizers applied have fallen every year since 2015, whereas those of manure have done the same after 2016; however, the decline in fertilizer use is more conspicuous, reflected in the rise in the manure-to-chemical-fertilizer ratio starting in 2015. The decrease in fertilizer use since 2015 can be attributed to the *Action Plans to Achieve Zero Growth of Chemical Pesticides and Fertilizers by 2020* (Ma and Zheng, 2022). The Chinese



Source(s): NBSC and FAOSTAT

Figure 1.
Banana production in the four provinces and national average in China

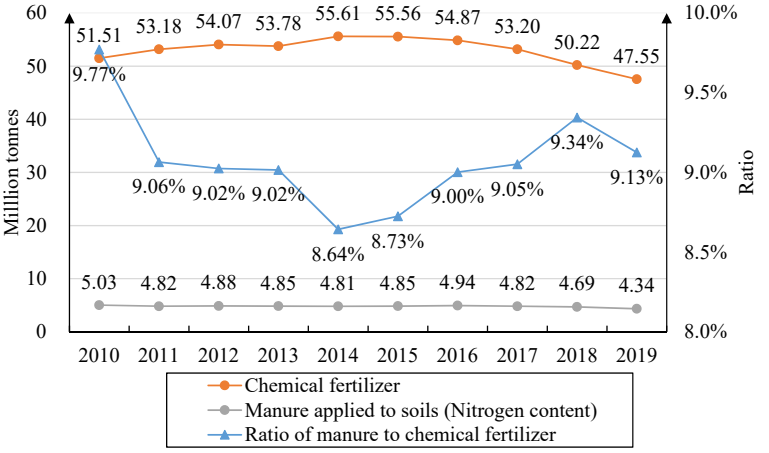


Figure 2.
Quantities and ratios of chemical fertilizer and manure in China

Source(s): FAOSTAT

government implemented the *Action Plan* in 2015 to mitigate the adverse effects of fertilizer overuse—the data suggest that this plan has been successful.

Indeed, in recent years, farmers have lessened their use of chemical fertilizers and manure. However, it is unclear how this reduction has affected the yields of specific crops. Thus, this study bridges an important gap in the literature by providing insights into the association between OSA-CF ratios and banana yield.

3. Method and data

3.1 Method

As alluded to in Section 1, the OSA-CF ratio was calculated as follows:

$$\text{OSA-CF ratio} = \frac{\textit{Expenditure on organic soil amendments}}{\textit{Expenditure on chemical fertilizers}}. \tag{1}$$

Because the effect of OSA-CF ratios on banana yields likely depends on how much chemical fertilizers a farmer uses, we also disaggregated chemical fertilizer expenditure into five quintiles, with Quintiles 1 and 5 representing farmers who spent the least and the most on chemical fertilizers. Disaggregating the data in this fashion allowed us to condition the effects of OSA-CF ratios on how much money was spent on chemical fertilizers. As the ratios can change due to variations in expenditure on OSAs, chemical fertilizers, or both, conditioning on chemical fertilizer expenditure generates ratios that change mainly due to changes in expenditure on OSAs. Then, we estimated the impact of the OSA-CF ratio on banana yields using the baseline regression,

$$Y_i^{\tau} = \alpha_i + \beta_i OSA\_CF\_ratio_i + \sum_{m=1}^{15} \gamma_{im} X_{im} + \varepsilon_i \; for \; \tau = 1, 2, 3, 4, 5, \tag{2}$$

where Y_i^{τ} denotes the banana yields obtained by farmers in chemical fertilizer quintile τ. OSA_CF_ratio$_i$ refers to the OSA-CF ratio used by the farmer i as defined in Equation (1). X_{im} represents m ($m = 15$) control variables capturing farmer and household-level characteristics (e.g. age, gender, education, and household size), production inputs variables (i.e. labor, seedlings, pesticides, and machinery), and location variables at the provincial level. α_i is a constant. β_i and γ_{im} are parameters to be estimated. ε_i is an error term. Equation (2) was estimated using ordinary least squares (OLS).

We implemented an alternate method to understand the associations between OSA-CF ratios and banana yields by creating a categorical variable, *TR*, representing four categories of the OSA-CF ratio, one comprising farmers using only chemical fertilizers and the remaining three based on OSA-CF ratio tertiles. This approach not only served as a robustness check to confirm the results obtained from estimating Equation (2) but also allowed us to view different ranges of OSA-CF ratios as separate treatments. As it is not often feasible for farmers to finely calibrate the ratios to optimize yields and minimize costs, examining the relationship between ranges of OSA-CF ratios and yields can provide practical insights to farmers.

Another issue that warrants attention is the potential endogeneity of OSA-CF ratio tertiles. Because farmers decide whether to apply organic soil amendments and how to combine them with chemical fertilizers, their fertilizer application decisions tend to be influenced by unobserved factors (e.g. motivations for using fertilizers, preconceived notions about OSAs, and aptitude for farming). Thus, the endogeneity of the OSA-CF ratio tertiles should be addressed.

Accordingly, following the IV-based two-stage predictor substitution (2SPS) method, we regressed the OSA-CF ratios on a vector of control variables (X_i) and an instrumental variable (IV_i). The regression is expressed in Equation (3):

$$\text{OSA\_CF\_ratio}_i = \delta_i X_i + \zeta_i IV_i + \theta_i, \tag{3}$$

where OSA_CF_ratio_i is as defined earlier. δ_i and ζ_i are parameters to be estimated; θ_i is the error term.

We used a synthesized IV, defined as the average OSA-CF ratio of other households in the same county as that of the farmer. Synthesized IVs have been used in several recent studies (Ma *et al.*, 2022; Oskorouchi and Sousa-Poza, 2021; Zheng *et al.*, 2021b). Our choice of the IV is motivated by the importance of peer influence in shaping behaviors and decisions and social learning theory, according to which observation plays a critical role in learning. Farmers in rural China take cues from their friends, relatives, and neighbors regarding farming practices. Tips and tricks exchanged between peers inform farming practices (Apetrei *et al.*, 2024; Borrelli *et al.*, 2018; Tran *et al.*, 2018). Thus, a farmer residing in a county with high chemical fertilizer use will likely apply more chemical fertilizer than another who lives in a county where farmers tend to use low levels of chemical fertilizer. We confirmed the validity of the IV using the Cragg-Donald Wald *F* statistic and the Stock–Yogo weak identification test critical values (Stock and Yogo, 2005). The *F* statistic of 27.03 was greater than the 10% critical value of 16.38, lending credence to the strength of the IV. Given the theoretical plausibility and the statistical evidence discussed above, we conclude that the IV is valid [2].

We used OLS to estimate Equation (3) and predict OSA_CF_ratio_i. Then, we defined the variable TR based on the predicted variable as follows:

$$TR = \begin{cases} 0, \textit{if expenditure on OSAs is zero} \\ 1, \textit{if predicted OSA\_CF\_ratio}_i \in \textit{Tertile}\,1 \\ 2, \textit{if predicted OSA\_CF\_ratio}_i \in \textit{Tertile}\,2 \\ 3, \textit{if predicted OSA\_CF\_ratio}_i \in \textit{Tertile}\,3. \end{cases} \tag{4}$$

The four categories are analogous to four treatments, and Tertiles 1, 2, and 3 denote low, medium, and high OSA_CF_ratio_i, respectively. Modeling the effects of different combinations of OSAs and chemical fertilizers on banana yields using an ordinal categorical variable allowed us to examine the effects of applying different levels of OSA-CF ratios relative to using only chemical fertilizers. Then, for each of the five quintiles τ, we estimated Equation (5),

$$Y_i^{\tau} = \sum_{n=1}^{3} \varpi_{in} TR_{in} + \sum_{m=1}^{15} \psi_{im} X_{im} + \vartheta_i \; for \; \tau = 1, 2, 3, 4, 5, \tag{5}$$

where TR_{in} is an ordinal categorical variable capturing whether a farmer applied a low, medium, or high OSA-CF ratio. Given that we had four categories, we left out farmers who did not apply any OSAs from the regression equation; this is the base category with reference to which we interpreted the results for the low, medium, and high categories. ϖ_{in} and ψ_{im} are parameters to be estimated, and ϑ_i is the error term.

3.2 Data

3.2.1 Data source. The data used in this study were obtained from a household survey of banana farmers in China. The survey was conducted using a multistage sampling approach between July and October 2019. The first stage involved selecting three major banana-producing provinces: Hainan, Yunnan, and Guangdong.

The three provinces have notable differences. Guangdong has the largest economy of all the provinces in China; Hainan's economy is one of the smallest—the GDP of the former was around 13 trillion yuan compared to around 680 billion of the latter in 2022. Yunnan's GDP was around 2.90 trillion yuan in the same year. The GDP per capita in Hainan, Yunnan, and Guangdong were 66,602 yuan, 61,716 yuan, and 101,905 yuan, respectively (NBSC, 2023). As for the industries in the three provinces, Guangdong has a thriving manufacturing sector, while tourism and agriculture have a strong presence in Hainan and Yunnan; Yunnan also has a sizeable mining sector. Climatically, Guangdong has a humid subtropical climate with short, dry, and mild winters and hot, humid summers. Yunnan has temperate summers and mild winters; however, its southern part has a tropical climate where temperatures can rise above 30°C in the summer. Last, Hainan, the southernmost province of China, has a tropical climate. Even in the winter, temperatures in the province can exceed 20°C. Because of its exposure to typhoons, it is also prone to flooding.

In 2022, the agricultural output in Hainan, Yunnan, and Guangdong was 227.2 billion, 663.6 billion, and 889.2 billion yuan, respectively (NBSC, 2023). In the same year, 0.39 million, 1.83 million, and 2.08 million tons of chemical fertilizers were used in the three provinces. These provinces have also instituted diverse policies to encourage organic fertilizer use. Hainan, for instance, has launched a comprehensive plan (2021–2025) targeting the reduction of chemical pesticides and fertilizers, aiming to promote 4.23 million tons of organic fertilizers by 2025. Guangdong plans to conclude 260 field experiments on the effects of fertilizers and chemical fertilizer utilization rates in 2023. In Yunnan, a "*leader*" selection activity for enterprise standards in the organic fertilizer sector was conducted in 2023.

In the second stage of the survey, three to five counties in each province were randomly selected. The third stage involved randomly selecting two towns from each county. Then, one to two villages were randomly chosen from each town. Finally, randomized samples of 10–20 banana-producing households in each village were obtained. Farmers who did not apply any chemical fertilizers during the cropping season overlapping with the timing of the survey were excluded. The dataset analyzed in this study comprised 616 farming households, each visited by an interviewer.

We relied on the expenditure on, rather than the weight of, fertilizers to construct the treatment variable, as the constituents of chemical fertilizers and OSAs differ (Ma and Zheng, 2022). For example, although the constituents of commercial fertilizers are known (they are published on the labels), the components of farmyard manure are mixed and challenging to measure. Besides, farmers apply different combinations of OSAs and chemical fertilizers to improve yields and the quality of produce, making it all the more difficult to precisely measure the weight of different types of fertilizers and OSAs. Moreover, because farmers

generally pay more for a higher concentration of certain constituents of OSAs and chemical fertilizers, expenditure is a more precise indicator of OSA-CF ratios than weight. Expenditure captures not only variations in market prices but also the quantity of fertilizer applied.

The outcome variable is banana yield, measured in kg/mu. Following previous studies on the relationship between fertilizer use and crop yields (Emmanuel *et al.*, 2016; Freeman and Qin, 2020; Holden and Lunduka, 2012; Li *et al.*, 2023; Ma and Zheng, 2022; Zhang *et al.*, 2021; Zheng *et al.*, 2021a), we included a comprehensive set of control variables to capture individuals' and households' characteristics and regional factors. The variables describing individuals are household heads' age, gender, education, and farming experience. We used data on the household heads as they are generally responsible for and hold sway in production decisions. Studies have shown that their age, gender, education, and farming experience are associated with whether and how farming households use OSAs and chemical fertilizers (Zhang *et al.*, 2021; Zheng *et al.*, 2021a). As for the household-level variables, we included household size, whether the household comprised university students, and whether it owned a car. A household's size determines its labor endowments. Applying OSAs can be labor-intensive, often requiring farmers to hire labor, as household members alone may not be able to complete this task in a timely fashion on their own. The larger the household, the more labor at its disposal and the less likely it is to hire labor. Owning a car is a symbol of household wealth. Wealthy households are more likely to have the resources to purchase farming equipment and hire labor.

We also included two variables to encapsulate proximity and access to institutions that can help farmers meet their financial, social, and business needs: a household's distance to a credit source and the presence of a cooperative in the household's village or neighboring villages. Access to credit and technical services is pivotal to completing farming tasks, including applying fertilizers competently and efficiently (Wossen *et al.*, 2017). Farmers can use credit to purchase production inputs such as fertilizers. Cooperatives can help farmers borrow equipment, hire technicians, and learn skills they can incorporate into their farming practices. We also included provincial dummies to control for regional characteristics such as climate conditions, institutional arrangements, and socioeconomic conditions.

3.2.2 Descriptive statistics. Table 1 shows the descriptive statistics for different levels of OSA-CF ratios, determined based on Equation (2). The average ratios for the low, medium, and high groups were 0.22, 0.49, and 1.83, respectively. The minimum and maximum values of OSA-CF ratios for the low and medium groups ranged between 0.01 and 0.77, suggesting that the expenditure on OSAs was lower than that on chemical fertilizer among these two groups of farmers. In the group with the high OSF-CA ratio (i.e. Tertile 3), some farmers spent more on OSAs than chemical fertilizers. The highest ratio was 12.48.

The definitions and descriptive statistics of the variables used in this study are presented in Table 2. The average banana yield was 3.19 thousand kg/mu. The average OSA-CF ratio was 0.70, and around 17% of households did not apply OSAs. That almost a fifth of farming households used only chemical fertilizers speaks to the popularity of these inputs and points to opportunities to improve the uptake of OSAs. Households with low, medium, and high

	Observations	Mean	Median	SD	Minimum	Maximum
No OSAs	104	0.00	0.00	0.00	0.00	0.00
Low (Tertile 1)	173	0.22	0.25	0.09	0.01	0.33
Medium (Tertile 2)	169	0.49	0.50	0.12	0.34	0.77
High (Tertile 3)	170	1.83	1.34	1.48	0.78	12.48

Source(s): Authors own creation

Table 1. Descriptive statistics: OSA-CF ratio levels

Variables	Definitions	Mean (SD)
Dependent variables		
Banana yield	Banana yields (1,000 kg/mu)[a]	3.19 (2.84)
Independent variables		
OSA-CF ratio	Ratio of expenditure on OSAs to expenditure on chemical fertilizers	0.70 (1.06)
No OSAs	1 if a farmer does not use any organic soil amendments (OSAs), 0 otherwise	0.17 (0.37)
Low (Tertile 1)	1 if OSA-CF ratio is in Tertile 1 of OSA-CF ratio, 0 otherwise	0.28 (0.45)
Medium (Tertile 2)	1 if OSA-CF ratio is in Tertile 2 of OSA-CF ratio, 0 otherwise	0.27 (0.45)
High (Tertile 3)	1 if OSA-CF ratio is in Tertile 3 of OSA-CF ratio, 0 otherwise	0.28 (0.45)
Age	Age of household head in years	48.28 (9.90)
Gender	1 if household head is male; 0 otherwise	0.83 (0.37)
Education	Years of education of household heads	8.07 (3.13)
Farming experience	Years of farming experience of household heads	25.08 (11.65)
Household size	Number of household members	5.98 (2.38)
Student member	1 if household has a member who is a university student, 0 otherwise	0.19 (0.39)
Car ownership	1 if household owns at least one car, 0 otherwise	0.31 (0.46)
Distance to credit source	Distance in kilometers from one's residence to the nearest informal credit source (e.g. relatives or friends) or formal credit source (e.g. banks) (km)	5.89 (8.39)
Cooperatives	1 if there is one or more cooperative(s) in households' residing or neighboring village, 0 otherwise	0.49 (0.50)
Labor	Family and hired labor (100 days/mu)	0.77 (1.01)
Seedlings	Expenditure on seedlings (100 yuan/mu)	2.87 (2.86)
Pesticides	Expenditure on pesticides (100 yuan/mu)	5.25 (10.17)
Machinery	Expenditure on machinery (100 yuan/mu)	4.22 (8.35)
Hainan	1 if household is in Hainan, 0 otherwise	0.36 (0.48)
Yunnan	1 if household is in Yunnan, 0 otherwise	0.30 (0.46)
Guangdong	1 if household is in Guangdong, 0 otherwise	0.34 (0.48)
IV	Average OSA-CF ratio of other households (i.e. except for the sampled household) in the same county	0.70 (0.33)
Sample size		616

Note(s): SD denotes standard deviation. [a]1 mu = 1/15 hectare
Source(s): Authors own creation

Table 2. Variable definitions and descriptive statistics

OCA-CF ratios accounted for 28%, 27%, and 28% of the overall sample, respectively. On average, 83% of households had male heads; the average age and educational attainment of household heads were 48.28 years and 8.07 years, respectively. The sampled households had six members on average, and 36%, 30%, and 34% of the households were located in Hainan, Yunnan, and Guangdong, respectively.

Differences between the means of selected variables for the four groups are presented in Table 3. The *F* values in the last column of the table suggest that using OSAs was associated with higher banana yields. However, the mean banana yields declined as the OSA-CF ratio increased, changing from 3.66 thousand kg/mu in the low group to 3.01 thousand kg/mu in the high group. These results suggest that while applying OSAs improved yield, applying more was not always better. Among the four groups, the age and gender of the household heads showed no significant differences. In contrast, a higher education level of the household head was associated with a higher OSA-CF ratio. There were also substantial differences in farming experience, car ownership, and distance to a credit source. These observations highlight the importance of accounting for confounding factors when exploring the associations between OSA-CF ratios and banana yields.

Variables	No OSAs	Low (Tertile 1)	Medium (Tertile 2)	High (Tertile 3)	*F* values
Banana yield	2.56	3.66	3.28	3.01	3.61**
Age	48.88	48.83	47.53	48.10	0.64
Gender	0.87	0.83	0.84	0.81	0.48
Education	7.14	8.01	8.25	8.53	4.56***
Farming experience	27.91	25.10	25.04	23.37	3.31**
Household size	5.45	6.19	5.98	6.09	2.31
Student member	0.21	0.12	0.22	0.21	2.50
Car ownership	0.30	0.20	0.41	0.33	6.62***
Distance to credit source	8.79	5.40	5.04	5.45	5.18***
Cooperatives	0.55	0.43	0.54	0.46	2.02
Labor	0.73	0.78	0.81	0.76	0.16
Seedlings	2.57	2.93	2.51	3.37	3.06**
Pesticides	3.47	6.27	5.07	5.47	1.69
Machinery	3.54	3.34	4.98	4.79	1.60
Hainan	0.18	0.55	0.37	0.26	18.16***
Yunnan	0.58	0.12	0.28	0.31	24.10***
Guangdong	0.24	0.32	0.34	0.43	3.63**
IV	0.60	0.66	0.63	0.86	21.45***
Sample size	104	173	169	170	

Note(s): **$p < 0.05$, and ***$p < 0.01$
Source(s): Authors own creation

Table 3. Differences in the means of selected variables for the four groups

4. Results and discussion

Should farmers use only chemical fertilizers or apply combinations of OSAs and chemical fertilizers to increase yield? To answer this question, we estimate separate regressions for each of the five quintiles. First, we examine the effects of actual OSA-CF ratios on the banana yields using Equation (2). The results are reported in Table 4. They show that the coefficient of OSA_CF_ratio is positive and statistically significant for Quintile 2, suggesting that for banana farmers in this segment, increasing the OSA-CF ratio is associated with higher yields. In contrast, the coefficients for Quintiles 4 and 5 are negative and statistically significant. This indicates that raising the OSA-CF ratio may lower yields for farmers already spending relatively more on chemical fertilizers. Furthermore, the effects are the largest for those in the highest quintile of chemical fertilizer expenditure. Overall, the results in Table 4 point to a nonlinear, hump-shaped association between OSA-CF ratios and yields. The coefficient is statistically zero for Quintile 1. It is the highest for Quintile 2, the only quintile for which the association is positive and statistically significant. Finally, the associations turn negative for Quintiles 4 and 5.

	Dependent variable = banana yield (1,000 kg/mu)				
Variables	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
OSA_CF_ratio	0.022 (0.023)	0.064 (0.036)*	−0.130 (0.116)	−0.205 (0.099)**	−0.308 (0.131)**
Control variables	Yes	Yes	Yes	Yes	Yes
Constant	8.703 (0.497)***	7.285 (0.670)***	8.647 (0.720)***	8.041 (0.760)***	8.405 (0.466)***
Sample size	124	130	118	129	115

Note(s): *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$. Robust standard errors are presented in parentheses. The reference province is Guangdong
Source(s): Authors own creation

Table 4. Associations between OSA-CF ratios and banana yields for different chemical fertilizer expenditure quintiles

Next, we segment the data based on tertiles of OSA-CF ratios and ask whether combinations of OSAs and chemical fertilizers consistent with low, medium, or high OSA-CF ratios increase yield. Once again, in keeping with the disaggregated approach, we estimate separate regression models for each of the five quintiles and present the results in Table 5.

The changes in banana yields associated with Tertiles 1, 2, and 3 of OSA-CF ratios are reported with reference to the base group comprising farmers who did not use OSAs. The key insight is this: among farmers who spent relatively less on chemical fertilizers (i.e. Quintiles 1 and 2), higher OSA-CF ratios were associated with higher banana yields, whereas for those who spent relatively more on them (i.e. Quintiles 3, 4 and 5), having high OSA-CF ratios either left yields unchanged or compromised them. Let us delve deeper into the results.

The coefficients for each of the three categories of the OSA-CF ratio were positive and statistically significant for Quintiles 1 and 2, suggesting that a shift from using only chemical fertilizers to applying them in conjunction with OSAs was associated with higher banana yields. For farmers in Quintile 1, the expenditure on chemical fertilizers ranged between 1.44 yuan/mu to 27.78 yuan/mu; they spent 12.42 yuan/mu, on average (see Table A1 in the Appendix). Given such small expenditures, it is reasonable to assume that these farmers apply small amounts of chemical fertilizers to their crops. Should these farmers not apply OSAs, their crops may be deprived of necessary nutrients, leading to low yields. Thus, it is unsurprising that higher OSA-CF ratios, which can be achieved by increasing OSAs, were associated with improvements in yields for this group of farmers. In fact, farmers in Quintiles 1 and 2 who combined OSAs and chemical fertilizers such that the OSA-CF ratio was between 0.01 and 0.33 (see Table 1) had 792 kg/mu and 534 kg/mu higher yields, respectively, compared to those in the same quintile using only chemical fertilizers.

Our results are consistent with previous studies showing the positive effects of using a mixture of organic and chemical fertilizers on yields. For example, according to Liu *et al.* (2021), substituting chemical fertilizers with organic ones improved vegetable yields in China so long as the substitution rate did not exceed 70%. Zhai *et al.* (2022) also showed that substituting chemical fertilizers with organic ones improved grain yields in China. But in stark contrast with Liu *et al.* (2021), they suggested a significantly lower substitution rate, i.e. 15%, to maximize benefits in the short run. Li *et al.* (2021) found that partially substituting chemical fertilizers with bio-organic fertilizers improved banana yields.

The coefficients for the low, medium, and high tertiles of OSA-CF ratios for farmers in Quintiles 3 and 4 were statistically insignificant. The findings imply that applying OSAs did

Variables	Dependent variable = banana yield (1,000 kg/mu) Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Base group (no OSA)					
Low (Tertile 1)	0.792 (0.332)**	0.534 (0.239)**	0.203 (0.188)	0.432 (0.368)	0.079 (0.181)
Medium (Tertile 2)	0.700 (0.303)**	0.585 (0.256)**	0.199 (0.179)	0.548 (0.394)	−0.039 (0.186)
High (Tertile 3)	0.632 (0.293)**	0.357 (0.195)*	−0.082 (0.229)	0.076 (0.375)	−0.401 (0.194)**
Control variables	Yes	Yes	Yes	Yes	Yes
Constant	8.007 (0.561)***	7.023 (0.639)***	8.451 (0.712)***	7.810 (0.776)***	8.370 (0.498)***
Sample size	124	130	118	129	115

Table 5.
Associations of OSA-CF ratios with banana yields for different chemical fertilizer expenditure quintiles

Note(s): *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$. Robust standard errors are presented in parentheses. The reference province is Guangdong. The tertiles are categorized based on the predicted OSA-CF ratio. We first estimated the OSA-CF ratio as a function of a vector of control variables and the IV defined in Table 2. Then, the OSA-CF ratio variable (i.e. the dependent variable) was predicted and categorized into tertiles, with farmers who did not use any OSAs as the reference group

Source(s): Authors own creation

not affect the yields of farmers spending between 68 yuan/mu and 140 yuan/mu or those spending between 142.86 yuan/mu and 300 yuan/mu on chemical fertilizers (see the third and fourth rows in Table A1 in the Appendix).

The results for farmers spending the most on chemical fertilizers (i.e. Quintile 5) stand in stark contrast to the results for farmers in the bottom two quintiles. Not only did applying low and medium OSAs not improve yields for farmers in Quintile 5, but using a high OSA-CF ratio instead of only chemical fertilizers was associated with lower yields. This was the only group of farmers for which we observed a negative effect of higher OSA-CF ratios on banana yield. The coefficient for Tertile 3 in the last column of Table 5 indicates that incorporating OSAs into the input mix such that the OSA-CF ratio rose above 0.78 (see Table 1) was associated with a 401 kg/mu decline in banana yields. That farmers who were excessively reliant on chemical fertilizers suffered losses to their yields when using high ratios of OSA is suggestive. Excessive use of chemical fertilizers depletes the land of vital nutrients and biodiversity, making it progressively reliant on these fertilizers, rendering OSAs ineffectual.

It is reasonable to ask why farmers continued to use OSAs if doing so compromised yield. Not all farmers know the marginal gains in yield from applying different combinations of OSAs and chemical fertilizers. It is rare for smallholder farmers to run controlled experiments to determine the effects of different treatments; furthermore, they do not have access to data on other farmers' use of OSAs and chemical fertilizers and how these are associated with yields. Smallholder farmers rely mainly on experiential learning to optimize inputs and outputs. If farmers knew that using OSAs beyond a certain threshold compromised yield, they would not breach the threshold. Overall, increasing the OSA-CF ratio improved yields or left them unchanged for all other quintiles except for Quintile 5.

5. Conclusions, implications, and limitations

5.1 Conclusions

The adverse environmental effects of chemical fertilizers are apparent; so are their deleterious effects on human health. Yet, lured by the prospects of high yields, farmers continue to overuse these fertilizers. Although sustainable production to feed a growing global population necessitates shunning the overuse of chemical fertilizers, an abrupt switch to organic alternatives can be economically and socially perilous; the 2021 food crisis in Sri Lanka is a case in point. Instead, a measured and informed transition toward sustainable agriculture is in order, and the transition would entail a gradual shift from chemical fertilizers to OSAs. Nevertheless, how this shift will affect yields remains an open question. This study is devoted to answering this question.

Using IV-based 2SPS models, we analyzed survey data collected from 616 banana-producing households in southern China and investigated the associations between combinations of OSAs and chemical fertilizers and banana yields. We recognize that the effects of OSA-CF ratios on yields are likely to vary between farmers using different levels of chemical fertilizers. Therefore, we grouped farmers into quintiles based on their expenditures on chemical fertilizers before estimating the associations between OSA-CF ratios and banana yields. Furthermore, in addition to analyzing the associations between the actual values of OCA-CF ratios and banana yields, we examined which range of ratios improved yields for each quintile. Both sets of models produced directionally similar results.

The effects of different combinations of OSAs and chemical fertilizers on banana yields varied across different quintiles. When we considered the actual values of OSA-CF ratios, we observed a hump-shaped association between the ratios and banana yields. Segmenting the data into different tertiles showed that, for the first and second quintiles, low, medium, and high OSA-CF ratios improved banana yields relative to not using OSAs. Yields for farmers in the first quintile not using OSAs were 792 kg/mu lower than for those in the same quintile

applying a low OSA-CF ratio. The results were quite similar for farmers in the second quintile—applying a low OSA-CF ratio was associated with an increase of 534 kg/mu in banana yields for farmers in this group. For the fifth quintile, applying a high OSA-CF ratio instead of using only chemical fertilizers was associated with a 401 kg/mu reduction in banana yields. Even so, for this group, transitioning from not applying OSAs to using low and medium OSA-CF ratios did not affect banana yields.

5.2 Practical implications and recommendations

Our results have practical implications for banana farmers in southern China, a region contributing considerably to the global banana output. For banana farmers spending less than 66.67 yuan/mu on chemical fertilizers, achieving an OSA-CF ratio between 0.34 and 0.77 may maximize yield. In contrast, if farmers who spend more than 320 yuan/mu on chemical fertilizers incorporate OSAs such that the OSA-CF ratio reaches 0.78 or higher, their banana yields may decline. These farmers may consider applying combinations of OSAs and chemical fertilizers that are consistent with low or medium OSA-CF ratios. Over time, as the soil characteristics change, they may revisit the optimal combinations of OSAs and chemical fertilizers.

The results also point to some broader policy implications. We found that 17% of the sampled farmers did not use OSAs. Thus, policymakers would do well to advise such farmers to incorporate OSAs to improve yields while attenuating the adverse effects of chemical fertilizers. Second, 28% of the sampled farmers applied a low OSA-CF ratio. These farmers could double the OSA-CF ratio while maintaining yields and alleviating environmental stress.

That incorporating OSAs can improve yield and plant growth is consistent with previous studies conducted in China and globally (Li *et al.*, 2021; Opeyemi *et al.*, 2015; Pattison *et al.*, 2011; Shen *et al.*, 2015; Tabarant *et al.*, 2011; Zhang *et al.*, 2019). Policymakers should design and implement educational and awareness programs to inform farmers of the benefits of using OSAs. Disseminating evidence-based insights through such programs will make farmers more amenable to integrating OSAs into their farming practices. Collaborating with universities and scientific organizations to this end can help gain farmers' trust in the programs (Borrelli *et al.*, 2018). Furthermore, creating fora for farmers where they can gather and exchange ideas can also stimulate the adoption of environmentally friendly farming practices that are also conducive to increasing profits—our results, which suggest that farmers' decisions regarding inputs are influenced by those around them, chime with several previous studies (Apetrei *et al.*, 2024; Borrelli *et al.*, 2018; Tran *et al.*, 2018).

OSAs can play an integral role in growing bananas sustainably. By adopting OSAs, banana farmers can improve soil health and mitigate the adverse environmental effects of using chemical fertilizers. Many smallholder banana farmers are poor and may be disproportionately affected by climate change. Using OSAs can help farmers preserve soil quality and structure, making crops more resilient to climatic variations. Thus, OSAs can prove valuable as part of farmers' adaptation strategies to cope with changing environmental conditions. Governments would do well to espouse the use of OSAs to strengthen and develop rural societies. Furthermore, farmers who grow bananas sustainably may also access a growing base of environmentally conscious customers willing to pay a premium for their products.

Bananas are among the most popular fruits, cultivated mainly by smallholder farmers in Asia, Latin America, and Africa. Higher banana yields resulting from using OSAs can improve income and food security in rural regions by increasing the availability of this staple crop and, thus, reducing farmers' vulnerability to hunger and malnutrition. Given the scale of banana production in rural areas in developing countries, higher banana yields can significantly raise the living standards in these areas. For these reasons, sustainable agricultural practices should be promoted as part of multipronged sustainable development policies in China and globally.

Agricultural subsidies designed to improve the adoption of OSAs may help farmers transition away from chemical fertilizers. Due to supply chain disruptions and geopolitical turmoil in Eastern Europe, chemical fertilizer prices have risen sharply during the last two years—consequently, the relative price of OSAs has declined. Thus, farmers may be more amenable to substituting chemical fertilizers with OSAs. Because chemical fertilizer prices remain high, relatively less expenditure in the form of subsidies and grants to accelerate the uptake of OSAs would be required. Nevertheless, a measured transition is in order. Abrupt changes to agricultural policies and regulations attempting to expedite a move toward OSAs are ill-advised and likely to fail—the recent food crises\is in Sri Lanka is a case in point (Wijerathna-Yapa *et al.*, 2023).

5.3 Limitations and future research avenues

Last, we want to call attention to some limitations of this study. Our data comes from a cross-sectional survey focused on banana farmers. Because OSAs build soil nutrients and fertility over time, analysis based on panel data would help capture the dynamic effects of OSAs over the long term. Furthermore, our results provide insights into the associations between OSA-CF ratios and banana yields in southern China. These results may not translate well to other crops and regions, as the interactions between ecosystems, weather, soil, crops, and farmers are complex. More research should be devoted to understanding how different fertilizers affect crop yields globally. Such research will contribute to policies and practices to accelerate a transition to sustainable production.

Notes

1. Sustainable agriculture has various interpretations. According to the U.S. Code Title 7 (Section 3103), the term "sustainable agriculture" means an integrated system of plant and animal production practices having a site-specific application that will over the long-term: (A) Satisfy human food and fiber needs; (B) Enhance environmental quality and the natural resource base upon which the agriculture economy depends; (C) Make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; (D) Sustain the economic viability of farm operations; and (E) Enhance the quality of life for farmers and society as a whole (CornellLawSchool, 2023).
2. Expectedly, the coefficient of the IV was positive and statistically significant. Specifically, it was 0.93 with a p value of less than 0.01.

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Appendix

Table A1. Descriptive statistics for chemical fertilizer expenditure quintiles

	Observations	Mean	Median	Minimum	Maximum	SD
Quintile 1	124	12.42	12.50	1.44	27.78	7.26
Quintile 2	130	46.53	46.06	28.00	66.67	11.80
Quintile 3	118	101.23	100.00	68.00	140.00	21.42
Quintile 4	129	213.56	200.00	142.86	300.00	48.07
Quintile 5	115	676.21	500.00	320.00	2,500.00	435.78

Source(s): Authors own creation
Note(s): Chemical fertilizer expenditures are measured in yuan/mu

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