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Optimising sunflower yields: insights from meta-analysis on fertilisation impact and planting strategies for enhanced crop productivity in China

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Abstract: Sunflower serves as a valuable rotational crop, suitable for snack processing or sunflower seed oil extraction, proving to be a lucrative cash crop. To address sunflower yield uncertainties, this study employs meta-analysis to examine the impact of fertilisation. Utilising 41 studies and 392 pairs of observations based on four criteria, we found an overall 27% increase in sunflower yield with fertiliser application. Nitrogen (N), phosphorus (P), and potassium (K) individually applied raised yield by 23.37, 20.92, and 11.63%, respectively. Combined fertilisers (NP, NK, NP, and NPK) enhanced yield by 29.69, 28.40, 17.35, and 41.91%, respectively. Sunflower type minimally affects yield, while planting density significantly influences it. Combining local soil conditions and environmental factors with appropriate planting densities ensures maximum sunflower yield, fostering economic benefits for farmers. This study holds constructive implications for sunflower cultivation in China, contributing to increased yield.

Keywords: *Helianthus annuus* L.; production; soil fertility; heterogeneity

Helianthus annuus L., also known as sunflower, can be processed into snacks or used for extracting sunflower seed oil (Ailwar et al. 2020, Lakshman et al. 2020, Tangyu et al. 2022). Sunflower yield is a crucial economic factor in global crops (Baraiya et al. 2018, Ortiz-Hernandez et al. 2020). In 2019, the global sunflower planting area reached approximately 2.74 × 10^7 ha, yielding 56.1 million tons. China, ranking sixth in sunflower production globally (Guo et al. 2021), has a sunflower planting area of 590 000 ha, with edible sunflowers occupying 95% (Feng 2022). Despite this, domestic sunflower raw material demand is 1.5 to 1.6 million tons, while annual exports are 400 000 tons. The import scale of sunflower raw materials is increasing, further widening the gap between Chinese sunflower production and demand. As the demand for sunflower seeds rises in both domestic and international markets, farmers are increasingly eager to cultivate sunflowers, transforming the sunflower industry into a dynamic emerging sector in the Chinese agricultural economy.

Sunflowers are tall and grow rapidly, requiring high levels of nitrogen (N), phosphorus (P), and potassium (K). Optimal fertilisation is crucial for maximising sunflower yield, offering cost savings and efficiency. Nitrogen enhances stem and leaf growth, boosting the photosynthetic rate (Massignam et al. 2009, Zeng et al. 2010) and serving as a vital element in sunflower life cycles (Hao and Wang 2015). P fertiliser promotes sunflower root growth, fostering early maturity and robust crop grains (Macolino et al. 2013). Optimal K supply promotes crop productivity and growth (Zörb et al. 2014, Jákli et al. 2017); K fertiliser positively influences sunflower oil content and significantly impacts grain development (Weis et al. 2002). Despite the rapid growth of the sunflower industry in China, issues persist, such as low production efficiency, non-standard planting

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practices, and imbalanced fertilisation, leading to generally low sunflower yields. Therefore, investigating fertilisation practices is crucial for enhancing sunflower yield.

Sunflowers are of two main types: oil and edible. Sunflower is a pivotal global oil crop, seed oil constitutes 12% of global plant oil production (Rauf et al. 2017, Mahmood et al. 2019). It boasts an excellent fatty acid composition, with unsaturated fatty acids like oleic acid and linoleic acid comprising nearly 90%, devoid of cholesterol or toxic components (Francois 1996). Edible sunflowers, rich in crude protein, carotene, vitamins, and various unsaturated fatty acids, serve as a nutritious snack (Tangyu et al. 2022). Limited research on the yield impact of oil and edible sunflowers necessitates further in-depth exploration. Regulating planting density stands out among the critical cultivation factors influencing sunflower yield. It affects light, temperature, water, and growth processes throughout the sunflower's growth period (Wang et al. 2021, Liu et al. 2023). An appropriately increased planting density enhances photosynthetic utilisation efficiency and boosts sunflower yield. However, excessive density escalates lodging risk, significantly reducing yield. This study will analyse the effects of sunflower types and planting density on sunflower yield.

Sunflowers significantly contribute to China's edible oil supply and food production, particularly in economically less developed arid and semi-arid regions. The sunflower industry plays a crucial role in elevating farmers' income in these impoverished areas, aiding them in overcoming poverty and fostering prosperity. Meta-analysis is the statistical integration of research results from independent tests that clarify hypotheses (Glass 1976, Mullen and Hu 1989); the benefit lies in the accumulation of knowledge within a certain research field (Cohen 1992, Hunter 2004). Thus, this study aims to (a) conduct a pairwise meta-analysis to assess the impact of fertiliser application on sunflower yield and (b) investigate how sunflower types and planting density influence sunflower yield in China

MATERIAL AND METHODS

Data collection. The China National Knowledge Infrastructure (CNKI) and the Web of Science were searched for studies published through October 1, 2023, using the following keyword combinations: ("sunflower") AND ("yield" OR "production") AND ("yield" OR "production") AND ("fertilize" OR "fertilizer" OR "fertilization"). Inclusion in the meta-analysis required adherence to four criteria: (a) monoculture of sunflowers; (b) provision of experimental details (location, altitude, average annual temperature and precipitation, soil organic matter, total N, available P and K, planting density, yield, cultivated cultivars); (c) repetition of experiment two or more times; (d) reporting measures of sunflower yield mean, error [(standard error (SE), standard deviation (SD)] and sample size (*n*). For studies providing only SE, SD was calculated as follows: $SD = SE \times \sqrt{n}$. The missing SDs were estimated at 0.1 times the yield means (Luo et al. 2006). Following these criteria, 41 studies and 392 pairs of sunflower yield observations were included in the meta-analysis. Data extraction from graphs utilised "WebPlotDigitizer" (Burda et al. 2017). We also extracted the corresponding climate and altitude data from the WordClim website (http://worldclim.org/version2). We extracted the corresponding soil fertility data from the Global Soil Dataset for Earth System Modeling (http://globalchange.bnu.edu.cn/research/soilw) if not provided by the study. Fertiliser types included: N – nitrogen; P – phosphorus; K – potassium; NP – combined nitrogen and phosphorus; NK – nitrogen and potassium; PK – phosphorus and potassium; NPK – nitrogen, phosphorus, and potassium.

Data analysis. Publication bias was tested using Egger's regression test (i.e. the funnel plot method), with significant *P*-values indicating potential publication bias (Egger et al. 1997). The R (version 4.2.2) was applied for all statistical analyses, in which effect size and publication bias were estimated using the R package "metaphor". All tests used 0.05 as the significance level. Log-response ratios (lnRR) (Hedges et al. 1999) is a measure of effect size (ES), which was calculated as the difference between the mean values of fertilisation and non-fertilisation in sunflower yield. Response ratios were calculated as follows:

$$lnRR = ln\frac{Y_T}{Y_C} \quad (1)$$

where: Y_t – yield mean fertilisation value; Y_c – yield mean value of non-fertilisation. The variance (υ) of each individual lnRR was calculated as follows:

$$\upsilon = \frac{S_t^2}{N_t Y_t^2} + \frac{S_c^2}{N_c Y_c^2} \quad (2)$$

where: N_t – sample sizes of fertilisation groups; N_c – sample sizes of non-fertilisation groups; S_t – standard deviations of fertilisation groups; S_c – standard deviations of non-fertilisation groups.

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The percent change was computed as follows:

$$change\ rate = (\exp(lnRR) - 1) \times 100\% \quad (3)$$

A multivariate meta-analysis model was used to assess the overall responses, followed by using the mixed-effects meta-regressions, including categorical variable (sunflower species) and numerical variable (planting density, altitude, average annual temperature and precipitation, soil organic matter, total N, available P and K) as moderators for each response variable. For meta-regressions:

$$Q_t = Q_m + Q_e \quad (4)$$

where: Q_t – overall heterogeneity of data; Q_m – heterogeneity caused by a known factor (i.e. the moderator); Q_e – residual error variance. The Q_m – statistic indicates a Wald-type test of model coefficients, and a significant Q_m – statistic indicates that the moderators contribute to the heterogeneity in effect sizes (Viechtbauer 2010).

RESULTS

Publication bias of sunflower yield. Our results showed that $P > 0.05$ indicates that the funnel plot is symmetrical, with the results being less affected by publication bias (Figure 1).

Sunflower yield in response to fertiliser application. Fertilisation has a significant positive effect on the yield of sunflowers (Figure 2A, Table 1). The sunflower yield increased by 31.00% with fertiliser application compared to non-fertilised conditions on average (Table 1). Single N, P, and K fertilisers individually enhanced yield by 23.37, 20.92, and 11.63%, respectively. Combined fertilisers, i.e., NP, NK, NP, and NPK, increased yield by 29.69, 28.40, 17.35, and 41.91%, respectively. This indicates that combined fertilisation yields more than individual fertilisation, particularly with NPK.

Under the condition of applying nitrogen fertiliser alone, the yield of sunflowers can be increased to 180 kg/ha. While above 180 kg/ha, there is no significant effect on the yield increase of sunflowers. The highest yield increase is achieved when applying nitrogen fertiliser at 120–150 kg/ha (Figure 2B). Under the single application of phosphorus fertiliser, a significant positive effect was observed on the yield increase of sunflowers below 90 kg/ha, and below 60 kg/ha was more suitable (Figure 2C). Under the condition of applying potassium fertiliser alone, due to the problem of limited data, a yield of less than 60 kg/ha significantly increases sunflower production (Figure 2D).

The relationship between sunflower types and yield. The multivariate meta-analysis demonstrated a significantly positive impact of fertiliser application on sunflower yield, although this effect exhibited high heterogeneity among experiments (Q_t = 430 381.69, $P < 0.0001$). When considering sunflower types (oil and edible) through mixed-effects meta-regressions (Figure 3), there is weak evidence suggesting varia-

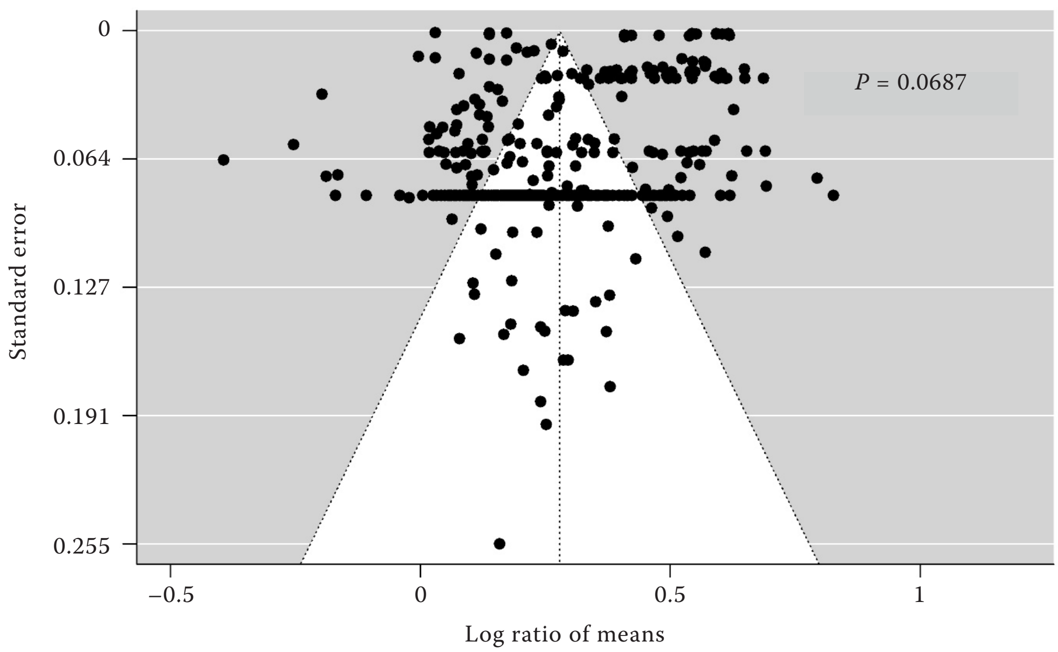

Figure 1. Publication bias of sunflower yield

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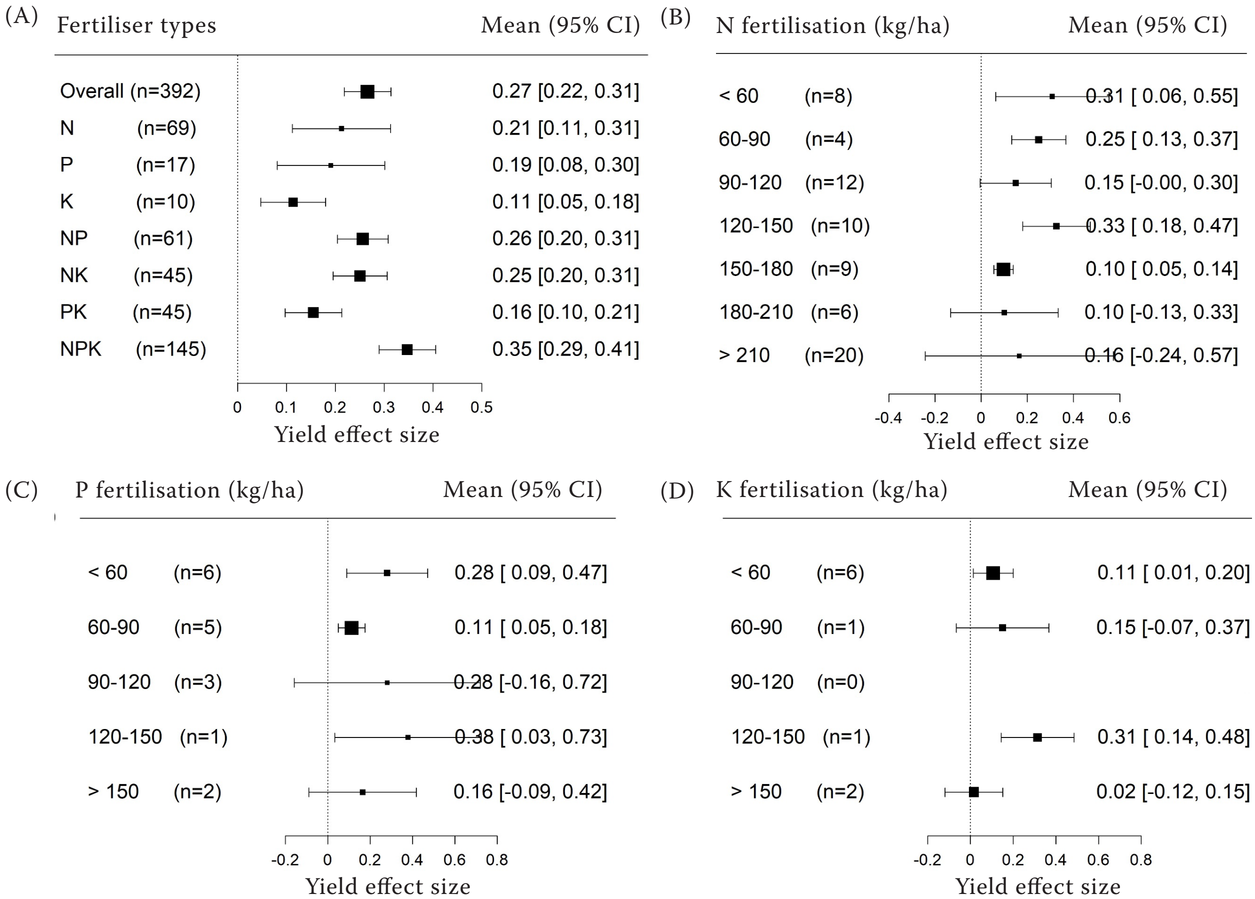

Figure 2. Weighted-mean effect sizes and 95%CI of (A) all fertilise types and (B) single nitrogen (N); (C) phosphorus (P), and (D) potassium (K) fertilisers effects. Fertiliser types: N – nitrogen; P – phosphorus; K – potassium; NP – combined application of nitrogen and phosphorus; NK – application of nitrogen and phosphorus; PK – application of phosphorus and potassium; NPK – application of nitrogen, phosphorus and potassium; *n* – observation number; the dotted line – zero

tions in yield benefits based on sunflower types (Q_m = 20.41, P < 0.0001).

The relationship between planting density, environmental factors and yield. Significant heterogeneity existed in sunflower yield effect sizes concerning planting density, altitude, average annual temperature and precipitation, with 382 782.06, 337 313.19, 380 373.37, and 314 181.24, respectively (Figure 4). At larger planting densities, the yield effect size consistently turned negative (Figure 4A). At larger altitudes, the yield effect size consistently turned positive (Figure 4B). The yield effect size consistently turned negative at larger average annual temperature and precipitation (Figure 4C–D).

The relationship between soil fertility and yield. Significant heterogeneity existed in sunflower yield effect sizes concerning soil organic matter, total N, available P and K, with 252 778.85, 370 131.61, 223 293.33, and 143 454.81, respectively (Figure 5). The yield effect size consistently turned positive at larger soil organic matter and total N (Figure 5A–B); at larger soil available P and K, the yield effect size consistently turned negative (Figure 5C–D).

Table 1. The rate of change in sunflower yield

Fertiliser types	Yield change (%)
Overall	31.00
N	23.37
P	20.92
K	11.63
NP	29.69
NK	28.40
PK	17.35
NPK	41.91

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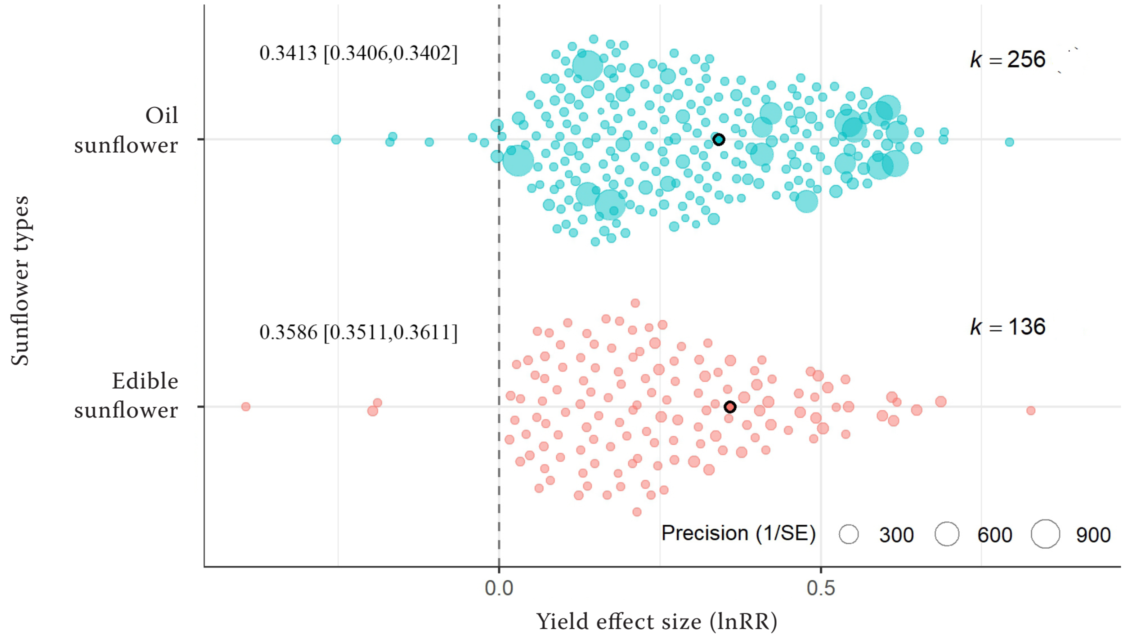

Figure 3. Sunflower yield relationship grouped by categorical covariates. Means and 95% confidence intervals for sunflower yield for two different sunflower types. Point size indicates the observation weight (weighted by 1/SE (standard error))

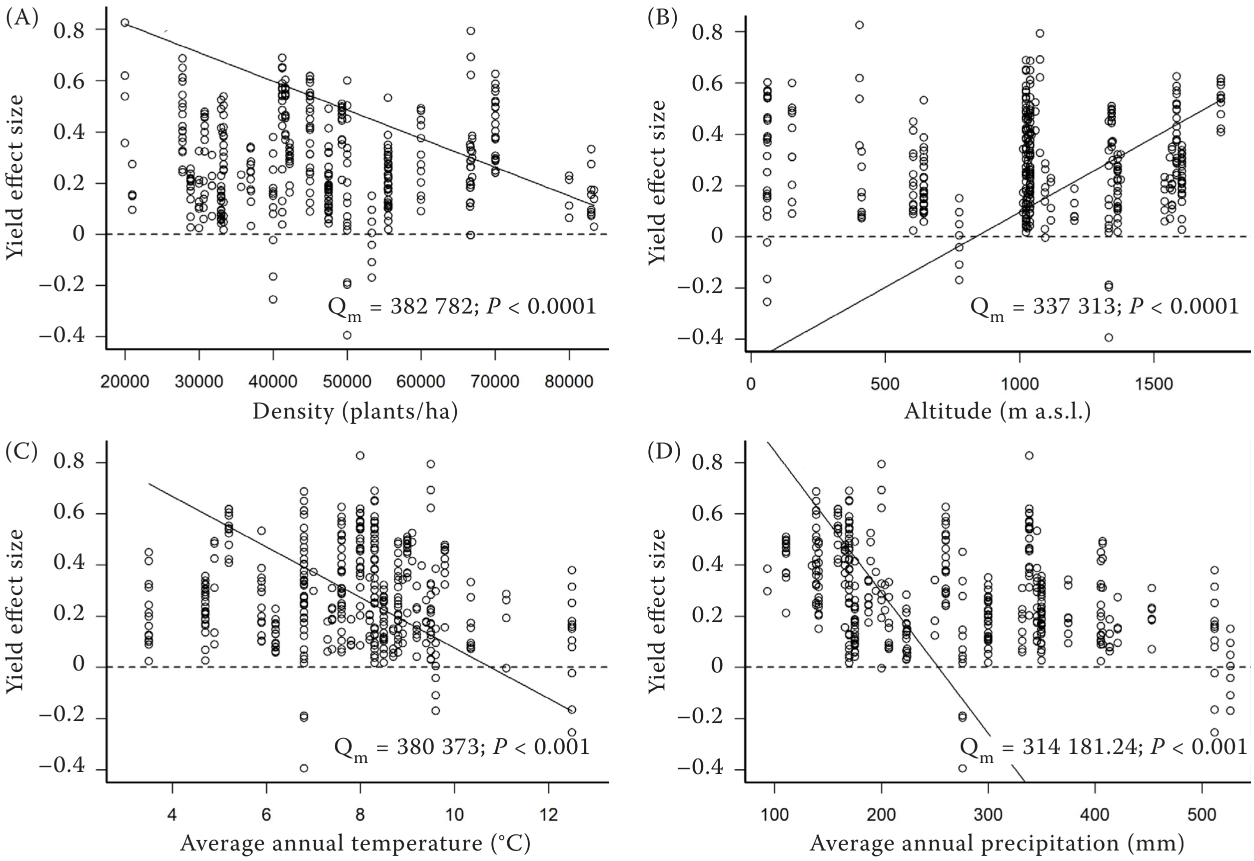

Figure 4. Meta-regression of sunflower yield effect size as a function of (A) planting density; (B) altitude; (C) average annual temperature and (D) precipitation. Q_m – Q-statistic, which renders information on whether the moderator illuminates any significant heterogeneity in the data

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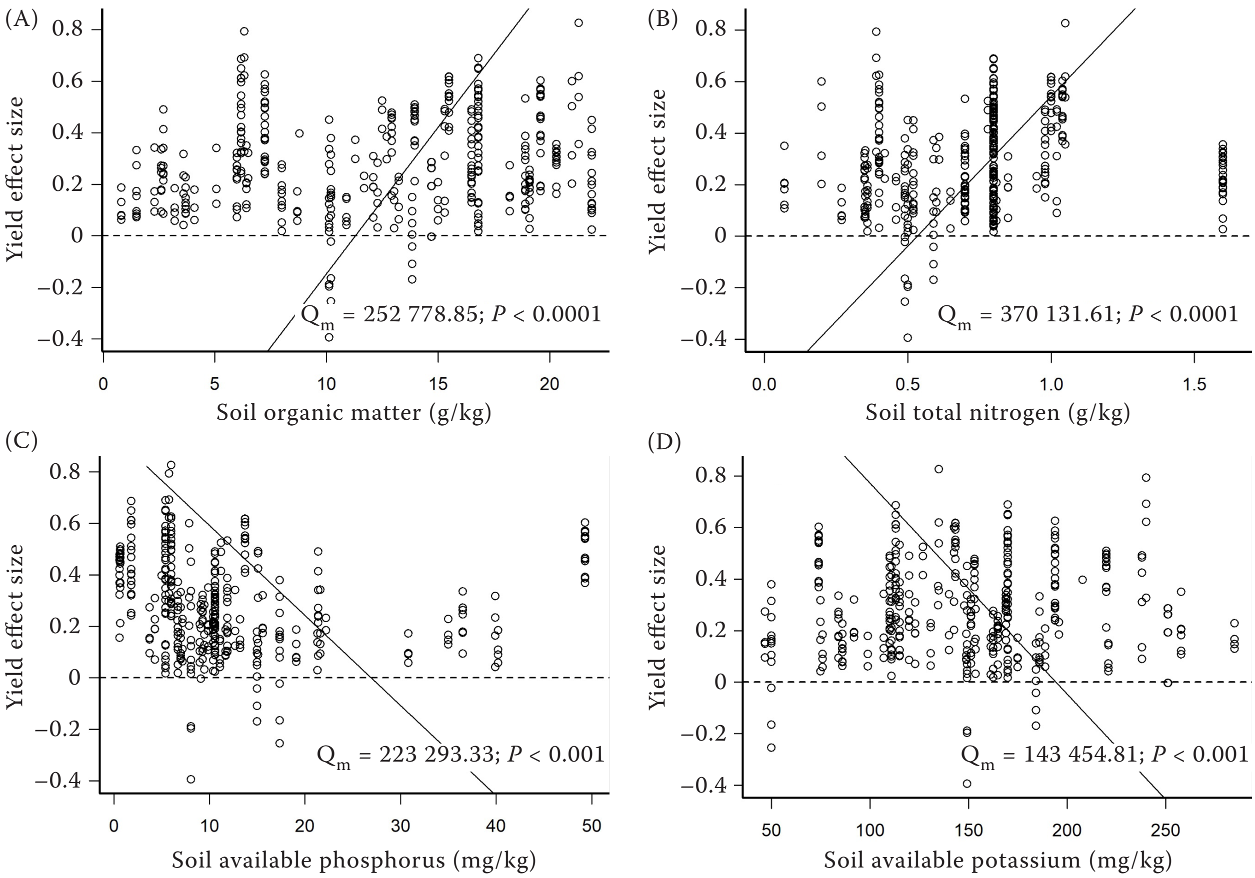

Figure 5. Meta-regression of sunflower yield effect size as a function of (A) soil organic matter; (B) total nitrogen (N); (C) available phosphorus (P) and (D) available potassium (K). Q_m – Q-statistic, which renders information on whether the moderator illuminates any significant heterogeneity in the data

DISCUSSION

N, P, and K limit sunflower yield as soil nutrients. Therefore, application of fertiliser is likely to increase sunflower yield significantly. The results indicate a 31% increase in sunflower yield with fertilisation compared to unfertilised conditions. Balanced N, P, and K fertilisation markedly enhances sunflower grain yield. Sunflowers utilise root and leaf absorption for nitrogen nutrient uptake, engaging in carbon and nitrogen metabolism for growth (Yuan et al. 2009, Duan et al. 2012). Increasing N fertiliser raises stomatal limit value, leaf transpiration rate, and chlorophyll content, improving light and energy efficiency (Zeng et al. 2010). In research, the application of nitrogen fertiliser alone increased the yield of sunflowers by 13.4–24.7% (Guo et al. 2019), which is close to the meta-analysis of 11.63–36.34% in this study. P fertiliser stimulates sunflower root growth and enhances crop grain plumpness (Macolino et al. 2013), and it can increase the weight of sunflower flower discs by 24.06% (Hu et al. 2013). K fertiliser reduces empty grain rates in oil sunflowers and increases 1 000-grain weight (Weis et al. 2002). A study has shown that applying potassium fertiliser to oil sunflower and edible sunflower yields an increase of 11.42% and 8.62%, respectively, compared to not applying potassium fertiliser (Li et al. 2018), which is similar to the results of applying potassium fertiliser alone in this study. N, P, and K are crucial and high-demand sunflower life elements. Previous research indicates N fertiliser's primary impact on sunflower yield (Volkmar et al. 1998, Guo et al. 2019). Our findings align, emphasising the greater influence of single nitrogen fertiliser on improving sunflower yield compared to individual phosphorus and potassium fertilisers.

China is located in the northern hemisphere, and as latitude decreases (i.e., from north to south), temperature and precipitation gradually increase,

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as altitude increases, temperature and precipitation decrease (Xiang et al. 2023, Zhou et al. 2023, Li and Liu 2024). Any temperature increase after the critical limit may result in a substantial decline in physio-morphic expressions, leading to a decrease in sunflower yield (Kaleem et al. 2010). Honeybees were mostly active during the days without rain; excessive precipitation affects bee pollination and thus affects sunflower yield (Puškadija et al. 2009). Soil nutrition status plays a decisive role in crop pollination, floral resources, flowering crops' physiological responses and productivity (Phillips et al. 2018, Tamburini et al. 2019). The input of nitrogenous fertilisers and irrigation water can be saved by increasing soil organic matter content, which positively impacts crop yield (Lal 2020). The increase in nitrogen fertiliser input will increase crop biomass, increase soil organic matter, and indirectly increase soil total N content (Wang et al. 2015). Excessive or insufficient soil available phosphorus content is not conducive to crop growth and development; crops grow well when the available phosphorus content is sufficient (Meng et al. 2022). Soil-available potassium plays an important role in plant growth. In areas with sufficient potassium, fertilisation or not will have a significant impact on the available potassium content in the soil, so it will not have a significant effect on crop growth and development (Ge et al. 2012). Therefore, when fertilising sunflowers, it is necessary to consider the local environment and soil fertility conditions in order to avoid wasting fertilisers and protect the environment.

Overall, this study demonstrated that combined fertilisation yields higher results than single fertilisation. In sunflower cultivation in China, the use of fertilisers lacks scientific precision (Qian et al. 2015). Over-application of 20% phosphorus fertiliser in North China and Northwest China, coupled with less than 30% potassium fertiliser demand, has led to a 15% decrease in sunflower production (Tuo et al. 2010). Appropriate application of N, P, and K significantly enhances sunflower grain yield, aligning with this study's findings; NPK combined application increases sunflower yield by up to 41.91%. Research indicates that a NPK fertilisation ratio of 16-20-2 produces the highest yield (Zhang and Wang 2004). Determining the optimal amounts and ratios of N, P, and K is crucial based on local production conditions (Zhang et al. 2001). Soil types affect N, P, and K absorption by sunflowers (Volkmar et al. 1998). The considerable impact of N, P, and K on oil sunflowers' growth, development, yield, and quality necessitates establishing a reasonable type and quantity of these nutrients based on soil fertility levels. This measure is crucial for increasing sunflower grain yield, improving oil sunflower quality, reducing production costs, mitigating fertiliser pollution, and fostering sustainable development in sunflower production and the broader agricultural industry.

The types of sunflowers primarily serve edible and oil purposes, influencing yield, with no significant difference observed between them. Edible sunflowers exhibit a nitrogen absorption peak from budding to flowering, while phosphorus and potassium absorption peaks during flowering. In contrast, oil sunflowers experience N and K absorption peaks during budding and phosphorus absorption peaks from flowering to maturity (Hu 2011). In Inner Mongolia, China, under the condition of applying nitrogen fertiliser alone, the yield of edible sunflower is slightly higher than that of oil sunflower (Wang et al. 2020), which is similar to the results of this study. Thus, varying fertilisation strategies at distinct stages significantly affect yield in different sunflower types.

Under the current production level, improving sunflower yield and quality involves regulating the relationship between individual growth and population function. Planting density effectively achieves this regulation, as demonstrated in a study in China on sunflower yield under varying planting densities. The study found that higher densities corresponded to increased yield up to a planting density of 49 500/ha (Li et al. 2010). Research has found that increasing planting density reduces the thousand seed weight, husk percentage, and flower disc size of sunflowers but ultimately enhances yield (Süzer 2010). While low-density conditions result in a higher average grain weight, it does not compensate for the overall grain quantity difference (Barros et al. 2004). This study showed a close relationship between sunflower yield and planting density; as planting density increases, sunflower yield decreases. Studies show that the seed setting rate is lower under low planting density, and appropriately increasing planting density improves the seed setting rate, significantly boosting yield (Modanlo et al. 2021). However, excessive planting density often triggers nutrient competition among populations, early leaf shedding, and insufficient dry matter accumulation in the later stage, resulting in decreased yield components (single plant yield, thousand-grain weight, and seed setting rate), poor appearance quality, and reduced commercialisation

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potential (Ahmed 2012, Wang et al. 2020). Therefore, by aligning with local soil conditions, implementing strategic fertilisation, and optimising planting density based on natural conditions such as light and temperature, the maximum production potential of sunflower populations can be realised, thus enhancing overall quality.

The diameter of the sunflower head was identified as being strongly associated with the quantity of fertilised seeds and the mass of the seeds (Marinković 1992). Allowing for the effect of head diameter, a study in central western France found that pollinators had a positive effect on the number of fertilised seeds (Perrot et al. 2019); this correlation was likely attributable to the enhanced pollination success as the abundance of pollinators increased (Carvalheiro et al. 2011, Pisanty et al. 2014). Ibrahim (2012) found a negative correlation between plant densities (45 000 and 90 000 plants per ha) and head diameter (Ibrahim 2012), which is very similar to our study. But another study found that the number of sunflowers 7.6 plants per m^2 is relatively good (Perrot et al. 2019); in fields where plant density was high, there was a greater abundance of pollinators, which was likely due to the increased attractiveness resulting from the greater availability of resources, a phenomenon observed in other plant species as well (Delmas et al. 2016).

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