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Response of potato tuber yield to NPK fertiliser in China: a meta-analysis

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Abstract: Potato (*Solanum tuberosum* L.) is an economically significant food crop in China, and increasing tuber yield is a national priority. We conducted a meta-analysis utilising 180 studies and 1 583 pairs of observations to quantify the effects of fertilisation on potato tuber yield using data on climate, soil nutrients, and planting strategies. Compared with no fertilisation, fertilisation increased tuber yield by 33.64% overall. Applying single N, P, or K fertilisers increased yield by 33.64, 23.37, and 16.18%, respectively; combined NP, NK, and PK applications increased yield by 33.64, 36.34, and 19.12%, respectively. The greatest yield increase (49.18%) was achieved when NPK fertilisers were applied together. Average annual precipitation had the strongest effect on tuber yield, followed by cultivar identity and the availability of soil potassium. Under appropriate fertilisation regimes, tailoring planting strategies to local climate and soil nutrient status can maximise potato yield and improve economic returns. These findings have implications for future potato cultivation in China.

Keywords: crop productivity; macronutrient; environmental condition; production; heterogeneity

Potato (*Solanum tuberosum* L.) ranks as the fourth most important food crop worldwide after maize, rice, and wheat (Qin et al. 2016, Zhang et al. 2017). As a vital non-cereal crop, it plays a significant role in ensuring global food security. It is widely recognised for its high nutritional value, including substantial amounts of proteins, essential amino acids, vitamins, and minerals (Zaheer and Akhtar 2016, Zhang et al. 2017). This, coupled with its ease of digestion and suitability for large-scale production, has made potatoes the most widely consumed vegetable worldwide (Fernández-López et al. 2020). China is the world's leading producer of potatoes, ranking first in total output and cultivated area (Zhang et al. 2017) and accounting for approximately 25% of global production (Li and Chang 2021). Sustaining current tuber yields in China is thus critically important for supporting research efforts aimed at further increasing production.

Previous research indicates that fertiliser application is a key driver of soil fertility and an effective means of improving crop productivity (Zheng et al. 2019, Zhang et al. 2023). Nitrogen (N), phosphorus (P), and potassium (K) are the three primary macronutrients essential for crop growth and development (Kumari et al. 2022). A balanced application of N, P, and K is critical for enhancing both yield and quality in potato (Li et al. 2015). An adequate N supply promotes foliar growth, thereby facilitating photosynthesis and carbohydrate synthesis, both of which are essential for tuber development (Naumann et al. 2020). P deficiency can hinder energy-transfer processes, thereby negatively affecting tuber development and ultimately reducing yield (Stark et al. 2020). Imbalances or deficiencies in K may reduce tuber size and impair tuber quality (Gericke 2018).

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Potato yield is influenced by a combination of factors, including cultivar identity, planting density, and environmental conditions such as rainfall and temperature (Kooman et al. 1996a, b, Dalla Costa et al. 1997, Meng et al. 2025). Cultivars differ in their nitrogen-use efficiency, which can lead to variations in yield (Cohan et al. 2018). Moderate increases in planting density can increase plant and stem populations, leaf area index, and tuber number, thereby enhancing yield and quality (Caruso et al. 2013). Seasonal water deficits and the uneven distribution of precipitation across time and space are major constraints on potato yield in rain-fed systems (Qin et al. 2014). Temperature also regulates key physiological processes, such as photosynthesis, respiration, and the allocation of photoassimilates, that underlie growth and yield (Yang and Zhang 2006).

Given the increasing importance of potatoes both within China and outside of China, we conducted a meta-analysis to evaluate (*i*) the effect of N, P, and K fertiliser application on potato tuber yield, and (*ii*) the effects of climatic factors, soil nutrients, and planting strategies on tuber yield.

MATERIAL AND METHODS

Data collection. We searched the China National Knowledge Infrastructure (CNKI, https://www.cnki.net/) and the Web of Science (https://webofscience.clarivate.cn/wos/woscc/basic-search) for studies published up to 1 October 2025 using the following keywords: ("potato") AND ("yield" OR "production") AND ("nitrogen" OR "phosphorus" OR "potassium" OR "fertiliser" OR "fertilisation" OR "fertilise") AND ("China" OR "Chinese"). Studies were included in the meta-analysis if they met all the following criteria: (1) potatoes were grown in monoculture in mainland China; (2) yield data were reported for both control and fertilised treatments; (3) detailed experimental location information (at least village name or latitude/longitude, plus mean annual temperature and precipitation), soil nutrient data (soil organic matter, total N, pH, available P, and K), and planting strategies (planting density and cultivars) were provided; (4) at least three experimental replicates were performed; and (5) tuber-yield means with an error term (standard error (SE) or standard deviation (SD)) and sample size (*n*) were reported. For studies reporting only SE, SD was calculated as SD = SE × $\sqrt{n}$. Missing SDs were imputed as 0.1 × the mean yield during data preprocessing (Luo et al. 2006). Applying these criteria yielded 180 studies and 1 583 paired observations of potato tuber yield for meta-analysis. Where raw data were unavailable, data points were extracted from figures using WebPlotDigitizer (Burda et al. 2017). When climate information was not provided in the original studies, climate variables were obtained from the WorldClim database (http://worldclim.org/version2), and soil-fertility variables from the Global Soil Dataset for Earth System Modelling (http://globalchange.bnu.edu.cn/research/soilw). Fertiliser treatments were categorised as N, P, K, NP (N + P), NK (N + K), PK (P + K), and NPK (N + P + K).

Data analysis. We calculated log response ratios (lnRR) for each treatment-control pair and used these as the effect size in the meta-analysis (Hedges et al. 1999). Response ratios were calculated as follows:

$$lnRR = \ln \frac{Y_f}{Y_{nf}}$$

where: Y_f and Y_{nf} – mean potato tuber yields in the fertilised and control groups, respectively. The variance (υ) of each effect size was calculated as follows:

$$v = \frac{S_f^2}{N_f Y_f^2} + \frac{S_{nf}^2}{N_{nf} Y_{nf}^2}$$

where: N_f and N_{nf} – mean sample sizes of the fertilisation and non-fertilisation groups, respectively; S_f and S_{nf} – mean standard deviation of the fertilisation and non-fertilisation groups, respectively.

The yield percent change was computed as follows:

$$\text{yield change rate} = (\exp(\text{lnRR}) - 1) \times 100\%$$

We analysed the data using a multilevel linear mixed-effects model fitted with the 'rma.mv' function in the R package metafor (Viechtbauer 2010). We then fitted mixed-effects meta-regressions, including climatic variables (mean annual temperature and precipitation), soil nutrients (soil organic matter, total N, pH, available P, and available K), and planting strategies (planting density and cultivar) as moderators for each response variable. For the meta-regressions:

$$Q_t = Q_m + Q_e$$

where: Q_t – total heterogeneity in the data; Q_m – portion of heterogeneity explained by the moderator variable; Q_e – residual (unexplained) variance. The Q_m statistic corresponds to a Wald-type test of the model coefficients, and a statistically significant Q_m indicates that the moderators contribute significantly to explaining variation in the effect sizes.

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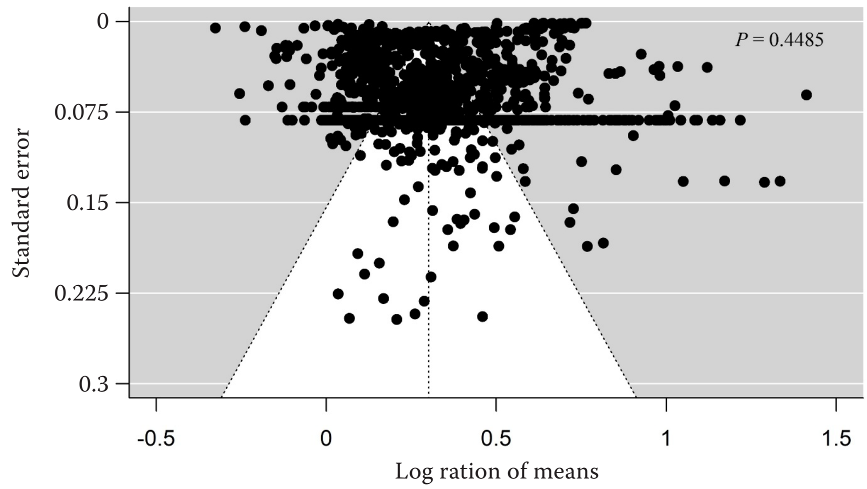

Figure 1. Funnel plot assessing publication bias for potato tuber yield effects

The nine explanatory variables were grouped into three categories: climatic factors, soil nutrients, and planting strategies. After assessing heterogeneity for each factor individually, the variable showing the greatest heterogeneity within each category was selected for multi-factor combination analysis.

Publication bias was evaluated using funnel plots, with Egger's regression test used to quantify plot asymmetry (Egger et al. 1997). Results with $P > 0.05$ were used to generate a symmetrical funnel plot, suggesting that the findings were unlikely to be strongly affected by publication bias (Figure 1).

Literature was managed in NoteExpress (Beijing, China), and data were compiled in Microsoft Excel 2016 (King County, USA). Statistical analyses and plotting were performed in R (Auckland, New Zealand). A significance level of 0.05 was used for all tests.

RESULTS

Effect of fertilisation on potato tuber yield. Overall, fertilisation had a significant positive effect on potato tuber yield (Figure 2, Table 1). Relative to no fertilisation, fertilisation increased the mean tuber yield by 33.64%. For single-nutrient applications, K produced the smallest gain (16.18%), followed by P (23.37%) and N (the largest, 33.64%). For combined applications, NPK resulted in the greatest increase (49.18%), followed by NK (36.34%), NP (33.64%), and PK (19.12%) (Table 1).

Response of potato tuber yield to climatic factors. The multivariate meta-analysis indicated a significant positive effect of fertiliser application on potato tuber yield; however, this effect showed substantial between-study heterogeneity

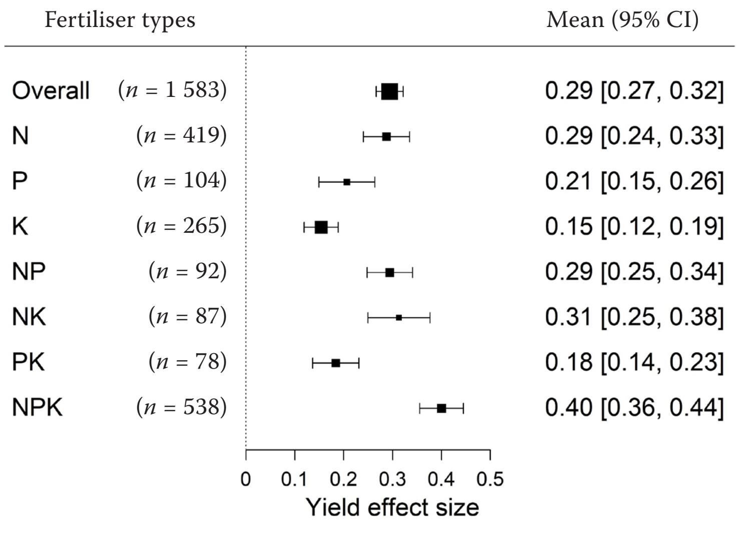

Figure 2. Effect sizes of fertilisation types on potato tuber yield. *n* – observation number; the dotted line – zero

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Table 1. Percentage change in potato tuber yield under different fertiliser regimes

Fertiliser types	Yield change (%) (95% CI)
Overall	33.64 [31.00, 37.71]
N	33.64 [27.12, 39.10]
P	23.37 [16.18, 29.69]
K	16.18 [12.75, 20.92]
NP	33.64 [28.40, 40.49]
NK	36.34 [28.40, 46.23]
PK	19.12 [15.03, 25.86]
NPK	49.18 [43.33, 55.27]

(Q_t = 636 929.52; P < 0.0001). Among climatic moderators, mean annual temperature and mean annual precipitation showed pronounced heterogeneity (Q_m = 303 070.80 and 602 311.19, respectively; Figure 3). Notably, precipitation alone explained 94.56% of the observed heterogeneity.

Relationship between soil nutrients and yield. The analysis revealed significant heterogeneity in the effect sizes of potato tuber yield associated with variation in soil organic matter, total N, available P, available K, and pH, as indicated by Q_m values of 53 563.38, 4 600.59, 113 422.10, 374 273.63, and 2 446.04, respectively (Figure 4A–E). As nutrient concentrations increased, soil organic matter, total N, available P, and available K were negatively correlated with the yield effect size (Figure 4A–D). In contrast, soil pH was weakly positively correlated with yield, explaining only 0.38% of the observed heterogeneity (Figure 4E).

Relationship between planting strategies and yield. Planting density showed significant heterogeneity in its association with potato tuber yield (Q_m = 148 182.02; Figure 4F). As planting density increased, the yield effect size of potato tubers decreased. As a categorical variable, cultivar encompassed 115 potato varieties and exhibited marked heterogeneity (Q_m = 561 474.16), accounting for 88.15% of the total heterogeneity.

Response of potato tuber yield to multiple factor combinations. Based on the heterogeneity attribut-

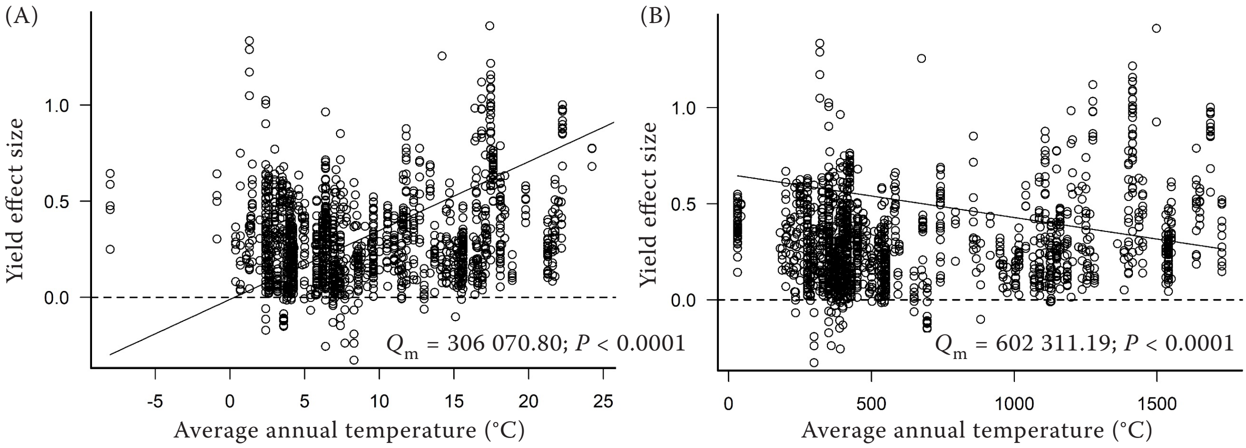

Figure 3. Effect of climatic factors on fertilisation response (InRR). Multivariate meta-analysis model of fertilisation response (InRR) as a function of (A) average annual temperature and (B) average annual precipitation. Q_m – Q-statistic, which provides information on whether the moderator explains significant heterogeneity in the data. The black solid line represents the trend curve; hollow circle represents fertilisation response (InRR); the dashed line represents the critical value of the effect size (InRR), Positive InRR = fertilisation increases yield, Negative InRR = fertilisation decreases yield

Table 2. Tests of moderators (Q_m) from mixed-effects meta-regressions with combined moderators

Factor combination	Q_m	P-value
Average annual precipitation + soil available K	375 402.40	< 0.0001
Average annual precipitation + cultivated cultivars	562 299.86	< 0.0001
Soil available K + cultivated cultivars	561 752.20	< 0.0001
Average annual precipitation + soil available K + cultivated cultivars	562 527.46	< 0.0001

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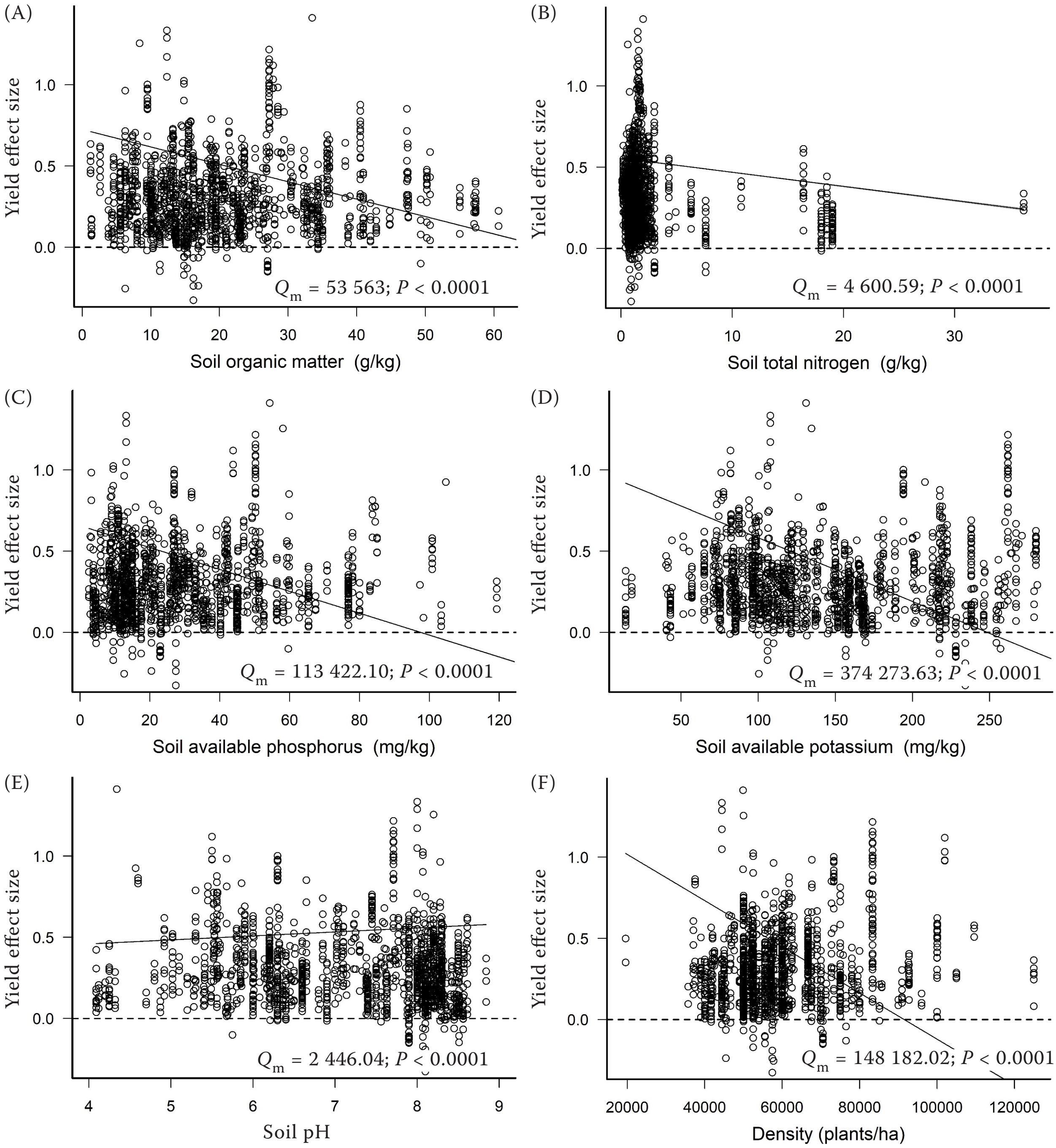

Figure 4. Effect of soil nutrients and planting density on fertilisation response (lnRR). Multivariate meta-analysis model of fertilisation response (lnRR) as a function of (A) soil organic matter; (B) total nitrogen; (C) available phosphorus; (D) available potassium; (E) soil pH, and (F) planting density. Q_m – Q-statistic, which provides information on whether the moderator explains significant heterogeneity in the data. The black solid line represents the trend curve; hollow circle represents fertilisation response (lnRR); the dashed line represents the critical value of the effect size (lnRR), Positive lnRR = fertilisation increases yield, Negative lnRR = fertilisation decreases yield

able to individual factors within each category, we selected the moderator that explained the greatest proportion of variation: mean annual precipitation (climate), soil available K (soil nutrients), and cultivar (planting strategies). The combination of mean annual precipitation + soil available K + cultivar

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explained 88.32% of the total heterogeneity. Pairwise combinations of mean annual precipitation + cultivar and soil available K + cultivar explained 88.28% and 88.20% of the variation in the data, respectively, whereas mean annual precipitation + soil available K explained the least (58.94%) (Table 2).

DISCUSSION

N, P, and K are the three essential macronutrients required for plant growth and development. In this study, applying N fertiliser alone increased yield by 33.64%, which is consistent with Xu's meta-analysis, which reports a 31.2% increase in potato yield with N fertilisation. The optimal N application rates are 135–270 kg/ha (Xu et al. 2020). Findings for K fertiliser were likewise consistent with Zhang's meta-analysis; the optimal K application rates are 76.1–225.8 kg/ha (Zhang et al. 2025). A meta-analysis from Finland showed that P fertilisation significantly enhanced crop yields, with an average increase of 11% relative to the control (Valkama et al. 2009). In India, a dose of 225 kg N/ha resulted in a significantly higher tuber yield than the state-recommended dose of 150 kg N/ha for Odisha (Mishra et al. 2025). In Ethiopia, P and K fertilisation have been shown to increase potato yield compared with unfertilised controls (Amare et al. 2025). In Florida, a two-year experiment similarly found that K fertiliser significantly increased potato tuber yield (Sidhu et al. 2025). Across different regions, potatoes exhibit similar requirements for N, P, and K; therefore, balanced nutrient availability is essential for maximising tuber yield.

Given that potatoes have a shallow root system, essential nutrients must be readily available within the immediate root zone (Amare et al. 2025). Nutritional demand for K and N in potatoes is particularly high (Westermann et al. 1994, Sidhu et al. 2025). Accordingly, in our study, NK fertilisation resulted in a larger yield increase than NP or PK. Among essential nutrients, N generally has the strongest effect on potato growth and productivity (Yadav et al. 2024). K is crucial for tuber development, regulating plant water relations, enzyme activation, and modulating source-sink dynamics across growth stages (Westermann 2005, Zörb et al. 2014). Optimal P management promotes early tuber initiation and accelerates maturation, thereby affecting tuber developmental age (Rosen et al. 2014). Given the indispensable roles of N, P, and K, the combined NPK application resulted in the largest yield increase in our analysis.

Available K in soil nutrients explains a large portion of the overall heterogeneity in potato yield effects. Within the soil-nutrient category, available K explained a large portion of the heterogeneity in potato yield effects. On China's Loess Plateau, available soil potassium has been shown to have the strongest influence on tuber yield (Wang et al. 2019), with a significant negative correlation between available K and yield, which is consistent with our results (Wang et al. 2019). Potatoes are relatively inefficient at K uptake; sufficient plant K is typically obtained only when applied K exceeds physiological requirements (Römheld and Kirkby 2010). Because potatoes are shallow-rooted, the direct influence of background soil nutrients can be moderated under fertilisation: with appropriate fertiliser regimes, the nutrient demands of plants can be met throughout the growth cycle. Appropriate mineral-fertiliser application regimes can therefore improve soil nutrient status and ultimately increase yields.

Temperature and precipitation, although not controllable during field production, are critical to potato growth and development. At higher latitudes, warmer mean temperatures are generally associated with faster development and longer growing seasons, which can enhance productivity (2016). This finding is consistent with the positive correlation between temperature and yield effect size observed in our study. However, further temperature increases may impair vine and root development, delaying tuber initiation and reducing final yield (Daccache et al. 2011). Conversely, exposure to low temperatures increases the risk of frost, which lowers growth performance and damages tubers (Haverkort and Verhagen 2008). Potato is drought-sensitive (Opena and Porter 1999), partly because soil compaction restricts root depth and density (Stalham et al. 2007). Soil moisture stress can markedly depress tuber yield (Zhao et al. 2016). It is therefore unsurprising that mean annual precipitation emerged as a major source of heterogeneity in yield effects in our analysis.

Planting density and cultivar identity also affected tuber yield. Within a certain range, increasing planting density increases the number of plants and stems per unit area, leaf area index, tuber number, yield, and quality (Caruso et al. 2013). In Northwest China, densities above 70 000 plants/ha or below 30 000 plants/ha are associated with reduced yields (Yang et al. 2021). In our dataset, when most densities were between 40 000 and 80 000 plants/ha, planting density was negatively correlated with the yield effect size, in-

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dicating that both overly high and overly low densities depress yield. Differences among cultivars also contribute to explaining observed patterns; although nutrient requirements among cultivars may be broadly similar, their yield and quality can vary (Amare et al. 2025). This variation might stem from genetic differences in resource allocation to tuber formation and dry matter accumulation (Naumann et al. 2020). Given China's vast geographic and climatic diversity, selecting cultivars suited to local conditions is essential for maximising tuber yield and farm profitability.

Among single-factor moderators in our analysis, mean annual precipitation (climate) was the strongest predictor of yield effects, followed by cultivar (planting strategy) and available soil K (soil nutrients). The joint combination of mean annual precipitation + available K explained relatively little variation, possibly because increased rainfall can exacerbate losses of plant-available K, thereby reducing yield increases. By contrast, combinations that included cultivar, such as mean annual precipitation + cultivar, available K + cultivar, and mean annual precipitation + available K + cultivar, each explained over 88% of total heterogeneity, highlighting the central role of cultivar identity. Selecting regionally adapted cultivars is therefore pivotal for maximising tuber yield and associated economic benefits.

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