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Research Article Open Access

Effects of Different Mulching Materials on Growth, Bulb Development, and Yield of Onion (*Allium cepa* L.) at Bardiya Nepal

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Abstract Onion (*Allium cepa* L.) is a high-value bulb crop cultivated extensively across Nepal. However, yield is limited by suboptimal soil moisture and temperature regulation, particularly under subtropical conditions. A field experiment was conducted during the rabi season (November 2024-April 2025) using a randomized complete block design with five mulching treatments (control, black plastic, rice straw, banana leaf, and sawdust mulch), each replicated three times. Growth and yield parameters were recorded at regular intervals after transplanting and at harvest. Plastic mulch significantly increased bulb yield (35.27 t/ha), showing a 91.5% improvement over the control (18.42 t/ha), while rice straw mulch produced the tallest plants and longest leaves. Rice straw mulch is recommended as a cost-effective and ecologically sustainable alternative for smallholder onion production under Nepal's subtropical Terai conditions.
Keywords Onion (*Allium cepa* L); Polyethylene mulch; Organic mulch; Bulb yield; Soil moisture conservation; Terai Nepal

1 Introduction

Onion (*Allium cepa* L., family Alliaceae) is one of the most important vegetable crops cultivated worldwide because of its high economic value and widespread use in household consumption and the food industry (Griffiths et al., 2002; Khokhar, 2014). Global onion production is close to 100 million tonnes annually, with South and Southeast Asia accounting for a significant share (FAOSTAT, 2023). In Nepal, onion is grown on approximately 19,346 hectares, producing about 334,047 metric tonnes each year. However, the average productivity remains around 17-18 t/ha, which is lower than the global average of 20-22 t/ha (MoALD, 2023). Improving onion productivity is therefore an important priority for meeting domestic demand and reducing dependence on imports.

One of the major factors limiting onion yield is its shallow and fibrous root system, which makes the crop highly sensitive to soil moisture stress and temperature fluctuations (Mutetwa and Mtaita, 2014). In the tropical Terai region of Nepal, high temperatures during the bulbing stage increase soil water loss, reduce nutrient uptake, and ultimately restrict bulb development (Brewster, 2008). Since many smallholder farmers have limited access to reliable irrigation, practices that conserve soil moisture are essential for sustaining onion production.

Mulching is an effective agronomic practice for improving the soil environment. By covering the soil surface, mulch reduces evaporation, moderates soil temperature, suppresses weed growth, and minimizes soil erosion (Bhardwaj, 2013; El-Beltagi et al., 2022). Organic mulches, such as rice straw, banana leaves, and sawdust, also improve soil structure and fertility as they decompose, whereas black polyethylene mulch provides greater short-term moisture conservation and soil warming (Ham et al., 1993; Lamont, 2005; Ramakrishna et al., 2006; Nair and Ngouajio, 2012).

Although the benefits of mulching have been reported for several vegetable crops, comparative studies evaluating different mulching materials for onion under the Terai conditions of Nepal are still limited. Most previous research has focused on crops such as garlic, potato, and leafy vegetables, with little information on the performance of locally available organic mulches compared with black polyethylene under the same field conditions (Tarara, 2000; Yimer, 2020). Therefore, this study was undertaken to evaluate the effect of different mulching materials on the growth and yield of onion under the agro-climatic conditions of Nepal's Terai region.

This study was therefore designed to: (i) evaluate the effects of four mulching materials and an unmulched control on growth dynamics across four developmental stages; (ii) assess their influence on bulb yield components and total fresh yield; and (iii) identify the most suitable mulching strategy for onion production in Bardiya District, Nepal.

2 Materials and Methods

2.1 Experimental site

The experiment was conducted at Shree Janata Secondary School, Bansgadhi Municipality, Bardiya District, Lumbini Province, Nepal (28.26° N, 81.52° E; approximately 150 m above sea level) during the rabi season from November 2024 to April 2025. The site has a subtropical monsoon climate with an average annual rainfall of approximately 1,600-1,900 mm, most of which occurs between June and September. During the crop-growing period, the mean monthly temperature ranged from approximately 11 °C in December to 35 °C in April.

The experimental field consisted of sandy loam soil with good drainage and a slightly acidic to neutral reaction (pH 6.0-7.2), which is considered suitable for onion cultivation. Based on the regional soil characteristics of Bansgadhi, Bardiya, the cultivated soils generally contain 1.5%-3.0% soil organic matter, 150-300 kg/ha available nitrogen, 15-35 kg/ha available phosphorus, 180-350 kg/ha available potassium, and have a bulk density of 1.3-1.6 g/cm^3. These soil properties indicate moderate fertility suitable for vegetable production. The experimental field had previously been cultivated with seasonal cereal crops and had not received any mulch treatment before the establishment of the experiment.

2.2 Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with five treatments and three replications, resulting in fifteen experimental plots, each measuring 5.0 m^2.

The treatments were as follows: T_1: Control (no mulch); T_2: Black polyethylene mulch (25 μm thickness); T_3: Rice straw mulch (5 cm thick); T_4: Banana leaf mulch (5 cm thick); T_5: Sawdust mulch (5 cm thick).

The organic mulching materials were collected locally and applied immediately after transplanting to maintain a uniform layer over the soil surface. Black polyethylene mulch was perforated at the designated planting positions before transplanting.

Forty-five-day-old seedlings of the locally grown onion cultivar 'Nasik Red' were transplanted on 20 November 2024 at a spacing of 15 cm × 10 cm (between rows × within rows). An inter-plot spacing of 0.5 m and an inter-block spacing of 1.0 m were maintained throughout the experiment.

2.3 Crop management

The field was ploughed twice to a depth of approximately 20 cm, followed by harrowing and leveling seven days before transplanting. Fertilizers were applied at the recommended rate of 80:60:60 kg N:P_2O_5:K_2O/ha using urea, diammonium phosphate (DAP), and muriate of potash (MOP). The full doses of phosphorus and potassium and 50% of the nitrogen were applied as basal fertilizer at transplanting, while the remaining nitrogen was top-dressed in two equal splits at three and six weeks after transplanting (WAT).

Flood irrigation was used throughout the experiment. All plots received the same amount of irrigation water at five-day intervals to ensure uniform water availability among treatments. Soil moisture was not monitored using soil moisture sensors, tensiometers, or the gravimetric method; therefore, the effects of mulching on soil moisture were inferred from crop growth and yield responses rather than direct soil moisture measurements.

Manual weeding was carried out at three and six weeks after transplanting in the control plots, whereas no additional weeding was required in the mulched plots because the mulch effectively suppressed weed growth.

2.4 Observations and measurements

Five representative plants were randomly selected from the central two rows of each plot and tagged after transplanting for recording growth observations. Plant height (measured from the soil surface to the tip of the longest leaf), leaf length (base to tip of the longest fully expanded leaf), and the number of leaves per plant were recorded at 30, 60, 90, and 120 days after transplanting (DAT).

At harvest, stem diameter (measured 2 cm above the bulb neck), bulb fresh weight, bulb length, equatorial bulb diameter, and root length were measured using a digital Vernier caliper (±0.01 mm) and a digital balance (±0.1 g). Total bulb yield was determined from the fresh weight of all harvested bulbs in each plot and converted to tonnes per hectare (t/ha).

2.5 Statistical analysis

The recorded data were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) using RStudio version 4.3.1. Before conducting ANOVA, the assumptions of normality and homogeneity of variance were verified using the Shapiro-Wilk and Levene's tests, respectively. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% level of significance. The coefficient of variation (CV%) was calculated to assess the precision of the experiment.

3 Results and Analysis

3.1 Plant height

Plant height increased progressively across all treatments from 30 to 90 DAT, with a characteristic decline at 120 DAT reflecting assimilate remobilization from foliar tissues to the developing bulb during senescence (Brewster, 2008). No significant treatment differences were detected at 30 DAT (Table 1). Significant effects were evident from 60 DAT onward.

Table 1 Effect of mulching treatments on plant height (cm) of onion (*Allium cepa* L.) at 30, 60, 90, and 120 days after transplanting (DAT)

Treatments	Plant height (cm)			
	30 DAT	60 DAT	90 DAT	120 DAT
Control	18.47b	35.62c	52.83d	48.91c
Banana leaf mulch	19.53ab	38.74bc	58.16c	53.45bc
Sawdust mulch	20.28ab	41.15b	61.42bc	58.07b
Rice straw mulch	21.74a	44.58a	67.93a	63.41a
Plastic mulch	21.19a	44.07a	65.28ab	61.83a
LSD ($p \leq 0.05$)	2.94	3.51**	4.23**	4.01***
CV (%)	7.86	4.42	3.81	3.64
Grand mean	20.24	40.83	61.12	57.13

Note: Means in a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). ** $p \leq 0.01$; *** $p \leq 0.001$. DAT: days after transplanting; LSD: least significant difference; CV: coefficient of variation

Rice straw mulch recorded the tallest plants at 60 DAT (44.58 cm), 90 DAT (67.93 cm), and 120 DAT (63.41 cm), closely followed by plastic mulch (44.07, 65.28, and 61.83 cm, respectively). The control consistently produced the shortest plants across all stages. The superiority of rice straw mulch for plant height is attributable to its dual role in moisture retention and progressive release of nitrogen and other nutrients as decomposition proceeds, augmenting the inorganic fertilizer program (Baten et al., 1995; Ramakrishna et al., 2006). These findings are consistent with Islam et al. (2007) and Mutetwa and Mtaita (2014), who documented superior plant height responses under straw mulch compared with bare soil in *Allium* crops.

3.2 Number of leaves per plant

Leaf count per plant was significantly influenced by mulching at all observation stages (Table 2). Plastic mulch consistently recorded the greatest leaf numbers: 4.73 (30 DAT), 7.00 (60 DAT), 9.27 (90 DAT), and 9.00 (120 DAT). The control produced the fewest leaves at every stage. Plastic mulch maintains stable, slightly elevated soil temperatures that accelerate meristematic activity and shorten plastochron intervals, thereby increasing leaf production rates (Tarara, 2000; Lamont, 2005). Rice straw mulch was statistically comparable to plastic mulch at 90 and 120 DAT, suggesting its nutrient-release profile increasingly supports rapid leaf development as the crop approaches the grand growth phase. These trends mirror findings of Kabir et al. (2013), who reported plastic mulch superiority for early-stage leaf development with straw mulch increasingly competitive at later stages.

Table 2 Effect of mulching treatments on number of leaves per plant of onion (*Allium cepa* L.) at 30, 60, 90, and 120 days after transplanting (DAT)

Treatments	Number of leaves per plant			
	30 DAT	60 DAT	90 DAT	120 DAT
Control	4.13b	5.67c	7.13c	7.47b
Banana leaf mulch	4.27ab	6.00bc	7.87bc	7.93ab
Sawdust mulch	4.20b	6.13b	8.07b	8.20ab
Rice straw mulch	4.53ab	6.67ab	8.80ab	8.73a
Plastic mulch	4.73a	7.00a	9.27a	9.00a
LSD ($p \leq 0.05$)	0.51	0.57**	0.75**	0.84**
CV (%)	6.32	5.14	5.51	6.87
Grand mean	4.37	6.29	8.23	8.27

Note: Means in a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). ** $p \leq 0.01$. DAT: days after transplanting; LSD: least significant difference; CV: coefficient of variation

3.3 Leaf length

Leaf length increased from transplanting through 90 DAT before declining at 120 DAT as assimilates were redirected to bulb storage organs (Table 3). Rice straw mulch consistently produced the longest leaves at all stages (25.88, 46.32, 58.14, and 42.37 cm at 30, 60, 90, and 120 DAT). Plastic mulch was statistically at par at all stages. The enhancement under rice straw mulch is attributed to improved nitrogen availability from mineralizing organic matter, which elevates leaf chlorophyll content and photosynthetic efficiency, sustaining leaf expansion (Baten et al., 1995; Nair and Ngouajio, 2012). The control consistently produced the shortest leaves, reflecting competitive water stress and nutrient immobilization associated with soil crusting in unmulched plots.

Table 3 Effect of mulching treatments on leaf length (cm) of onion (*Allium cepa* L.) at 30, 60, 90, and 120 days after transplanting (DAT)

Treatments	Leaf length (cm)			
	30 DAT	60 DAT	90 DAT	120 DAT
Control	22.53b	38.91c	46.07d	30.44d
Banana leaf mulch	23.94ab	41.72bc	49.53c	34.88c
Sawdust mulch	24.27ab	43.46ab	52.71bc	37.08bc
Rice straw mulch	25.88a	46.32a	58.14a	42.37a
Plastic mulch	25.17a	45.53a	55.92ab	41.14ab
LSD ($p \leq 0.05$)	2.21*	3.14*	3.88***	4.31***
CV (%)	5.24	4.33	3.97	6.22
Grand mean	24.36	43.19	52.47	37.18

Note: Means in a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). * $p \leq 0.05$; *** $p \leq 0.001$. DAT: days after transplanting; LSD: least significant difference; CV: coefficient of variation

3.4 Yield and yield-associated parameters

All yield parameters except root length were significantly affected by mulching treatments (Table 4). The absence of a statistically significant mulch effect on root length ($p > 0.05$) likely reflects high intra-block variability and the sensitivity of onion root architecture to micro-scale irrigation uniformity (Larkin, 2020).

Table 4 Effect of mulching treatments on yield and yield-related parameters of onion (*Allium cepa* L.) at harvest

Treatments	Stem Dia. (cm)	Bulb Wt. (g)	Bulb length (cm)	Bulb Dia. (cm)	Root length (cm)	Total yield (t/ha)
Control	0.89c	61.72e	4.28c	5.21d	10.38a	18.42d
Banana leaf mulch	1.11b	80.93cd	4.73bc	5.79cd	9.76a	22.14c
Sawdust mulch	1.06b	76.58d	5.19a	5.91bc	10.09a	23.87c
Rice straw mulch	1.28a	95.84b	4.97ab	6.53ab	10.68a	29.54b
Plastic mulch	1.41a	111.47a	4.83b	7.08a	11.14a	35.27a
LSD ($p \leq 0.05$)	0.19***	9.7***	0.33***	0.61*	1.97 ns	2.9***
CV (%)	5.92	6.24	3.82	5.17	10.91	5.86
Grand mean	1.15	85.31	4.80	6.10	10.41	25.85

Note: Means in a column followed by different lowercase letters differ significantly at $p \leq 0.05$ (DMRT). * $p \leq 0.05$; *** $p \leq 0.001$; ns: not significant. LSD: least significant difference; CV: coefficient of variation; Stem Dia.: stem diameter; Bulb Wt.: bulb weight; Bulb Dia.: bulb diameter

3.4.1 Stem diameter

Plastic mulch produced the widest stem diameter (1.41 cm), followed by rice straw mulch (1.28 cm), while the control recorded the smallest (0.89 cm). Pseudostem girth is closely correlated with overall plant vigor, vascular bundle density, and capacity for water and solute transport to the bulb (Ahmad et al., 2022). Banana leaf and sawdust mulches produced intermediate values (1.11 and 1.06 cm, respectively), reflecting their lower thermal insulation and slower nutrient contribution relative to plastic and straw mulches.

3.4.2 Bulb weight

Fresh bulb weight differed significantly among treatments ($p < 0.001$). Plastic mulch achieved the highest value (111.47 g), followed by rice straw mulch (95.84 g), banana leaf mulch (80.93 g), sawdust mulch (76.58 g), and the control (61.72 g). The 80.7% increase in bulb weight under plastic mulch relative to the control underscores the critical importance of consistent moisture supply and thermal regulation during the bulbing phase. These results corroborate Islam et al. (2007) and Najafabadi et al. (2012), who documented substantial bulb weight advantages under polyethylene mulch. The competitive performance of rice straw mulch reflects the combined benefit of moisture conservation and gradual nitrogen supply during storage organ filling.

3.4.3 Bulb length and diameter

Sawdust mulch produced the longest bulbs (5.19 cm), though statistically at par with rice straw mulch (4.97 cm). Elongated bulb form under sawdust is attributable to its high porosity and low bulk density when applied as mulch, improving aeration and reducing mechanical resistance to radial bulb expansion (Haque et al., 2003). Bulb diameter was greatest under plastic mulch (7.08 cm), followed by rice straw mulch (6.53 cm), and was lowest in the control (5.21 cm). Equatorial diameter is a primary determinant of commercial grade in onion markets, making the plastic mulch advantage economically significant (Najafabadi et al., 2012).

3.4.4 Total yield

Total fresh yield showed the strongest treatment differentiation (Table 4). Plastic mulch yielded 35.27 t/ha 91.5% advantage over the control (18.42 t/ha)—and was significantly superior to all other treatments. Rice straw mulch (29.54 t/ha) was the next highest, statistically distinct from banana leaf mulch (22.14 t/ha), sawdust mulch (23.87 t/ha), and the control. The superior yield under plastic mulch is a cumulative outcome of consistently higher leaf area index, improved photosynthetic duration, enhanced nutrient uptake efficiency, and reduced weed competition across the entire growth cycle (Lamont, 2005; El-Beltagi et al., 2022). The yield hierarchy plastic > rice straw > sawdust > banana leaf > control is consistent with reports from comparable subtropical environments (Ramakrishna et al., 2006; Mutetwa and Mtaita, 2014).

4 Discussion

4.1 Effect of mulching on vegetative growth

The results clearly showed that mulching improved vegetative growth compared with the unmulched control. Rice straw mulch produced the tallest plants and the longest leaves, while plastic mulch resulted in the highest number of leaves. These improvements suggest that mulching created a more favorable environment for onion growth during the growing season. Mulch generally reduces water loss from the soil surface and suppresses weed growth, allowing plants to use available water and nutrients more efficiently. Since soil moisture and temperature were not measured in this experiment, these factors cannot be confirmed directly, but they are likely to have contributed to the observed differences.

The better performance of rice straw mulch may also be related to its gradual decomposition during the cropping period. As the mulch breaks down, it can improve the soil surface environment and provide a small amount of nutrients to the crop. Similar responses have been reported by Ramakrishna et al. (2006), who found that straw mulch improved crop growth by conserving soil moisture and enhancing soil conditions. Likewise, Mutetwa and Mtaita (2014) reported improved vegetative growth of onion under organic mulching compared with bare soil.

4.2 Effect of mulching on bulb development and yield

The improvement in vegetative growth was reflected in bulb development and final yield. Plastic mulch produced the highest bulb weight, bulb diameter, stem diameter, and total bulb yield, whereas the control consistently recorded the lowest values. Onion bulb development depends largely on the plant's ability to produce and transfer photosynthates from the leaves to the bulb. Therefore, treatments that supported better leaf growth were also able to produce larger bulbs and higher yields.

Rice straw mulch also performed well and produced significantly higher yield than the control. Although its yield was lower than that of plastic mulch, the difference was relatively small considering that rice straw is an inexpensive and locally available material. This suggests that rice straw can be a practical alternative for farmers who wish to improve onion production without relying on plastic mulch.

Root length was not significantly affected by the treatments. This indicates that the increase in yield was more closely related to improvements in above-ground growth and bulb development than to changes in root elongation.

4.3 Comparison with previous studies

The findings of this study agree with several earlier reports showing positive effects of mulching on onion production. Islam et al. (2007) and Najafabadi et al. (2012) also reported higher bulb yield under plastic mulch than under bare soil. Similarly, Ramakrishna et al. (2006) found that organic mulches improved crop performance by reducing evaporation and creating more favorable soil conditions.

However, the magnitude of yield improvement observed in the present study differs from some previous reports. Such differences are expected because crop response to mulching depends on several factors, including climate, soil type, irrigation method, cultivar, and mulch characteristics. In this experiment, onion was grown under the subtropical conditions of western Nepal using flood irrigation, whereas many previous studies were conducted under different environmental conditions and irrigation systems. These differences may explain the variation in yield response among studies.

4.4 Agronomic implications

Among the tested mulching materials, plastic mulch was the most effective for maximizing onion yield. Nevertheless, its use also raises concerns about the disposal of polyethylene after harvest and the possibility of plastic residues remaining in agricultural fields.

Rice straw mulch offered a good balance between productivity and sustainability. Although it produced a lower yield than plastic mulch, it substantially outperformed the control and other organic mulches. Because rice straw is readily available in the Terai region and decomposes naturally, it can serve as a practical and environmentally friendly option for smallholder farmers. Therefore, farmers seeking maximum yield may prefer plastic mulch, whereas those aiming for a low-cost and sustainable production system may find rice straw mulch to be a suitable alternative.

4.5 Limitations and future research

The findings of this study should be interpreted in light of several limitations. The experiment was conducted at a single location during one growing season, and soil moisture, soil temperature, nutrient dynamics, and weed biomass were not measured directly. Consequently, the mechanisms responsible for the beneficial effects of mulching could not be verified experimentally.

Future research should evaluate these mulching materials across different locations and growing seasons to determine whether the observed responses remain consistent under varying environmental conditions. Measuring soil moisture, soil temperature, and nutrient availability would help explain the processes responsible for improved crop performance. In addition, economic analyses and assessments of the environmental impacts of plastic mulch would provide useful information for developing practical recommendations for onion growers in Nepal.

5 Conclusion

This study provides comprehensive evidence that mulching materials significantly influence the growth trajectory, bulb development, and marketable yield of onion under subtropical conditions in Chitwan, Nepal. Plastic mulch consistently maximized yield parameters, achieving a total fresh yield of 35.27 t/ha nearly double the control yield of 18.42 t/ha with the highest bulb weight (111.47 g), bulb diameter (7.08 cm), and stem diameter (1.41 cm). Rice straw mulch emerged as the strongest-performing organic alternative, particularly for plant height and leaf elongation, with a total yield of 29.54 t/ha representing a 60.4% improvement over the control.

Sawdust mulch demonstrated a specific advantage in promoting bulb elongation (5.19 cm), potentially valuable in markets favouring elongated bulb forms. Banana leaf mulch and the unmulched control consistently underperformed across all parameters. Given documented concerns regarding microplastic accumulation, soil contamination, and disposal challenges associated with long-term polyethylene mulch use, rice straw mulch is recommended as the preferred sustainable option for smallholder onion production in Nepal’s Terai region. Where maximum productivity is the primary objective and plastic waste is responsibly managed, plastic mulch remains the most effective single intervention.

Future research should investigate the economic feasibility and cost-benefit ratios of mulching systems at different farm scales, long-term effects of organic mulches on soil health and microbial communities, performance across multiple onion varieties, and the potential of biodegradable plastic mulches as transitional alternatives to polyethylene.

Authors’ contributions

BK conceived and designed the study, conducted the research, interpreted the results, and prepared the original manuscript. AG performed the data analysis, assisted with data interpretation, and critically reviewed the manuscript. SC managed the experimental field, supervised field operations, and collected the experimental data. All authors read and approved the final manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research Article Open Access

From Tunnels to Transformation: Evidence of Livelihood Enhancement through Protected Vegetable Farming in Meghang, Nuwakot

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Abstract This study was carried out from March 2025 to June 2025 to assess the contribution of tunnel based vegetable farming in household income and livelihood enhancement in Meghang Rural Municipality, Nuwakot. The data was taken from five wards namely Panera (ward No.6), Samari (ward No.5), Kimtang (ward No.4), Deurali (ward No.3), Bungtang (ward No.2). A total of 100 farmers were selected through simple random sampling, and data were collected using household surveys and interviews. According to the study, farming community was dominated by male farmers (68%) and the majority were between the ages of 30 to 50. The majority of respondents were involved in vegetable farming as prime occupation and source of income. Tomato was the dominant crop grown under tunnels, and most farmers adopted improved practices such as drip irrigation and mulching. Majority of farmers relied on agro vets for hybrid seeds, applied FYM with chemical fertilizers, and had built medium sized, 6*12 m tunnel covered with 90 GSM plastic sheets. About 38% of the farmers who produced vegetables in tunnels earned more than NRs. 3 lakhs annually. About 23% of income was saved and was mostly used for health, education, and food. However, farmers faced challenges such as high initial investment, limited access to inputs, and market dependency. Overall, plastic tunnel farming has the potential to support household income generation and livelihood improvement in the study area.
Keywords Farming; Income; Livelihood; Tunnel; Vegetable

1 Introduction

Vegetable farming is an important income generating activity for smallholder farmers in Nepal. It plays significant role in Nepal's agricultural economy as a valuable cash crops and provides quick cash, improves household income, food security and livelihood conditions among smallholder farmers. As compared to traditional and cereal based farming systems, vegetable production provides opportunity for higher economic return within short production cycle and limited land resources while having higher demand in the market. Vegetables are considered important for both nutrition and economic reasons. Vegetables are abundant in nutrients, minerals and vitamins. Vegetables consist of phytochemicals which are antioxidant and anti-inflammatory in nature, these properties help reduce the risk of chronic diseases such as diabetes, cancers, obesity or cardiovascular diseases (Abobatta, 2021).

Vegetable production, yield, and cultivation area have all steadily increased in Nepal's agriculture sector during the last ten years. While production climbed by 21% in the fiscal year 2020-21, the cultivated area increased by nearly 16% between 2011-12 and 2020-21. But in the last year, productivity has only gone up by 4.38%. With the exception of the fiscal years 2016-17, 2019-20, and 2020-21, the cultivated area, production, and productivity were all steadily rising overall (Ghimire et al., 2023).

According to the Food and Agriculture Organization (FAO's) 2024 data, global fruit and vegetable production reached 2.1 billion tonnes in 2023, which represents a 1% rise compared to 2022 (FAO, 2024). In Nepal, the vegetable industry is the largest subsector, accounting for 80.09% of the country's total horticultural produce and 9.7% of its overall Agricultural Gross Domestic Product (AGDP). Over the past 20 years, Nepal's total per capita vegetable intake has grown from 60 kg to 128.04 kg (Gyawali et al., 2022). An estimated 3,243,521 households cultivate vegetables, with women leading 17% of these households (CASA, 2020).

Despite the growing significance of vegetable farming in Nepal, production is highly influenced by seasonal climate changes, particularly in the mid-hills and high-hills of Nepal. Farmers often face challenges such as disease and pest outbreaks, heavy rainfall, frost, low temperature and limited production opportunity during off-seasons. These challenges impact crop yield, market supply and profitability. Therefore, the adoption of protected cultivation technology including plastic tunnels has emerged as a potential approach to mitigate climatic constraints and boost vegetable production.

Growing out of season crops in a controlled environment within plastic tunnels is generally referred as tunnel farming. Usually, this kind of farming is employed to grow summer vegetables during the off seasons (Sarmah et al., 2022). With the use of these protected cultivation technologies, farmers can design controlled environments that are suited to the unique requirements of their crops, increasing crop quality, productivity, and resource efficiency. The most popular type includes shade houses, polyhouses, greenhouses, and others (Rana and Sahu, 2024). These structures help regulate temperature, conserve soil moisture, protect crops from frost, excessive rainfall and wind damages. These structures reduce the impact of adverse weather conditions and provide favourable environment, improves crop quality, fetch higher market price and extend production periods. According to Atreya et al. (2020), Nepal's estimated 1,000 hectares of protected farming, 70% are used for vegetable production and 30% are used for fruit and flower cultivation.

Protected vegetable cultivation is especially important for small holder's farmers in the mid-hill areas of Nepal, where restricted land and climate uncertainties hinder year round yields. Tunnel production allows farmers to cultivate high value vegetable crops like tomatoes, cucumbers, leafy greens with optimum utilization of land and resources. Studies have shown that tunnel technology contributes to improved crop productivity and supports livelihood improvement by increasing production opportunities and strengthening income generation among smallholder farmers (Kc et al., 2021).

Meghang Rural Municipality in the Nuwakot district is emerging as a significant area for vegetable production under tunnel technology. Due to favourable agro-climatic conditions and the growing farmers interest in protected vegetable cultivation, the area has been recognized as a vegetable production zone under the National Agriculture Modernization Program (NAMP). However, few studies have investigated the socio-economic impacts of plastic tunnel vegetable farming at a local level, particularly regarding farmer's production practices, marketing systems, and how they utilize the income generated for their livelihoods.

Therefore, this study aimed to assess the contribution of tunnel based vegetable farming to household income and livelihood improvement among smallholder farmers in Meghang Rural Municipality, Nuwakot. This study examined farmer's socioeconomic characteristics, tunnel production practices, vegetable marketing channel, income generation and major constraints affecting vegetable production.

2 Materials and Methods

2.1 Study area

The study was carried out in Meghang Rural Municipality, Nuwakot (Figure 1). Meghang is a Rural Municipality located in Nuwakot District of Nepal, it has total 6 wards and 98 square kilometers of geographical area, according to 2011 census, it had total population of 13,479 (Karki, 2019). The data was taken from 5 different wards namely, Panera (ward No.6), Samari (ward No.5), Kimtang (ward No.4), Deurali (ward No.3), Bungtang (ward No.2).

The research area represents a mid-hill agro ecological setting ideal for commercial vegetable cultivation. The area has a temperate climate with seasonal changes, where cold winter temperature and significant rainfall during the monsoon season frequently impact open-field vegetable cultivation. These climatic constraints lead farmers to utilize protected methods like plastic tunnels to prolong the growing season and enhance crop yield.

Agriculture serves as the primary source of livelihood in Meghang Rural Municipality, where farmers primarily engage in vegetable cultivation (tomato, cabbage, cauliflower, cucumber, potato as primary crops), livestock rearing, and diverse farming practices. The grown vegetables are sold via local collection systems, cooperatives, and middleman to nearby urban areas such as Kathmandu which is around a distance of 80 km.

The study area was selected purposively because the region has developed into a growing hub for vegetable production as part of the National Agriculture Modernization Program (NAMP) with a rise in the use of plastic tunnels for commercial vegetable farming.

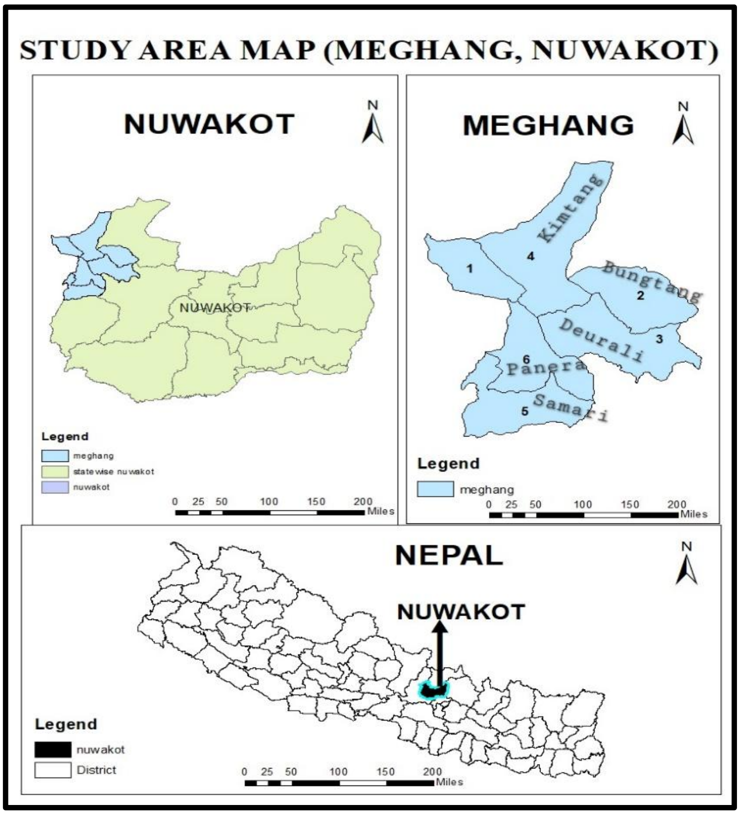

Figure 1 Map of Meghang Rural Municipality, Nuwakot, Nepal

2.2 Sample size

A household was considered as the sampling unit for the study. A total of 100 households were selected using a simple random sampling technique and the data were recorded from the respective farmers involved in vegetable production under plastic tunnels. The sample size was selected considering the availability of tunnel based vegetable growers, feasibility of household level data collection, time constraints and available resources while maintaining adequate representation of farmers involved in protected vegetable cultivation.

Due to the absence of a complete publicly available database, 100 households were selected using simple random sampling based on the available list of active tunnel vegetable growers and the feasibility of household level data collection. The chosen sample consisted of farmers with various socioeconomic status and farming sizes to reflect differences in tunnel structures, production methods, income generation, and marketing strategies.

2.3 Data collection

Primary data were acquired by direct personal interview and household survey using semi-structured questionnaires. An objectively prepared survey questionnaire was created to collect necessary primary data and information on the socioeconomic profile of vegetable growers under plastic tunnels, demographic information about family members, farmer landholdings, farming practices, and income status.

The secondary data were gathered from a variety of published and unpublished materials from different sources. These materials contain annual reports from Ministry of Agriculture and Livestock Development (MoALD), Nepal Agriculture Research Council (NARC), and District Agriculture Development Office (DADO), as well as research papers, articles, and journals.

2.4 Data analysis

The gathered data were organized, coded and analyzed using Microsoft excel. Descriptive statistical tools were used to summarize the characteristic of respondents and their production practices. Frequency and percentage analysis were used to describe the socioeconomic characteristics, tunnel structures, irrigation methods, marketing channel and income categories. Results were presented using tables, figures, and graphical representations.

The study mainly used descriptive analysis because the objectives was simply to assess the current status, production practices, income patterns, and perceived livelihood contribution of tunnel based vegetable farming among surveyed households.

3 Results and Analysis

3.1 Socio-demographic information of the respondents

The socio-demographic information of the respondents is presented in (Table 1). Among the 100 respondents, 68% were male and 32% were female farmers. The majority of the respondents (40%) belonged to active age group of 30-50 years followed by those between 50-70 years (30%), 20-30 years (20%), and above 70 years (10%).

Table 1 Socio-demographic information of the respondents

Demographic characters	Category	Percentage (%)
Gender	Male	68
	Female	32
Age group	20-30	20
	30-50	40
	50-70	30
	70 above	10
Literacy status	Illiterate	22
	Literate	18
	Below SLC (School Leaving Certificate)	34
	Plus 2	19
	Graduate	7
Occupation	Farming	60
	Business	10
	Service	9
	Wage labour	13
	Others	8
Total land under plastic tunnel cultivation	0.05-0.25 ha	37
	0.25-0.50 ha	40
	More than 0.50 ha	23

Regarding educational status, most respondents had basic education. About 34% had education below the School Leaving Certificate (SLC) level, 19% had completed higher secondary education, 7% had a university degree, while 22% were illiterate.

In terms of occupation, a significant 60% of the population were engaged in farming activities as primary occupation while a relatively smaller percentage were engaged in wage work, businesses, and services, at 13%, 10%, and 9%, respectively. In terms of land allocation for tunnel cultivation, 40% of farmers cultivated vegetables on small to medium-sized plots (0.25-0.50 ha), while 37% cultivated on less than 0.25 ha and 23% cultivated on more than 0.50 ha. These findings indicate that the tunnel vegetable farming in the study area is mainly practiced by small and medium scale farming households.

3.2 Plastic tunnel structures

3.2.1 Types of tunnel used by the respondents

Farmers used different types of plastic tunnels based on their farm size, investment capacity and crop to be planted. Among the respondents, 84% used medium sized tunnel with a height of 2-2.5 m, while 10% used high tunnel (4-5 m) and 6% used low tunnels (up to 1 m) (Figure 2).

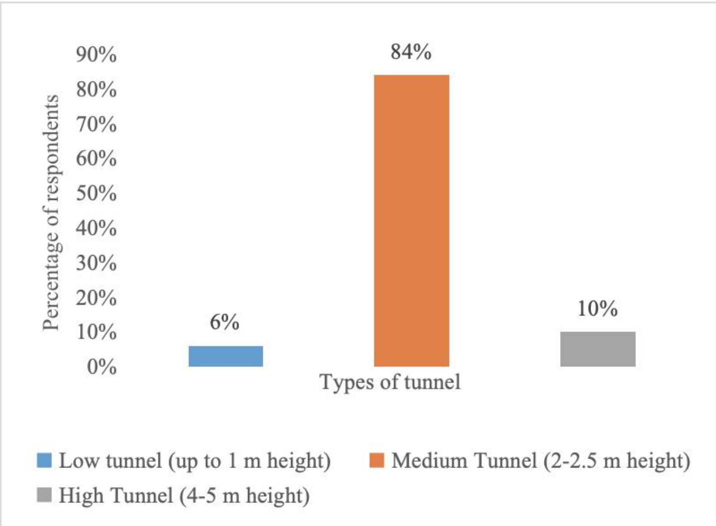

Figure 2 Types of tunnels used by the respondents

The most common structure respondents used were medium tunnels as they are suitable for crops like tomato and cucumber. Protected structures such as walk-in tunnels are common for cultivating commercial vegetables as they provide a controlled environment and allow efficient crop management (FAO, 2013).

3.2.2 Grams per Square Meter (GSM) of plastic used by the respondents

The majority i.e. 60% of the farmers used 90 GSM plastic sheets, followed by 120 GSM (25%), 200 GSM (7%), and 8% of the other farmers used others GSM (50 GSM, 70 GSM, 150 GSM) and microns plastic (100 micron, 200 micron) (Figure 3).

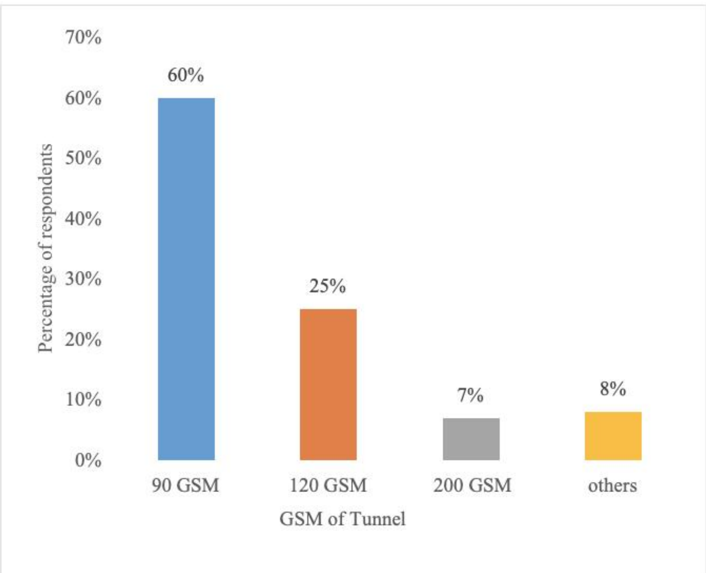

Figure 3 GSM of plastic used by the respondents

The thickness of plastic is important factor in durability of tunnel especially in areas exposed to rain, strong wind and hailstorm. Plastic materials ranging from 70-120 GSM are commonly used for protected structures in Nepal (Bhusal et al., 2022).

3.2.3 Size of the plastic tunnel used by the respondents

Different tunnel sizes were observed among farmers. The most common tunnel size was 6*12 m, adopted by 35% of respondents. Other tunnel sizes included 6*18 m (20%), 6*10 m (15%), 6*15 m (12%), and other sizes (18%) include 12*15 m, 15*18 m, 18*24 m of plastic tunnels (Figure 4).

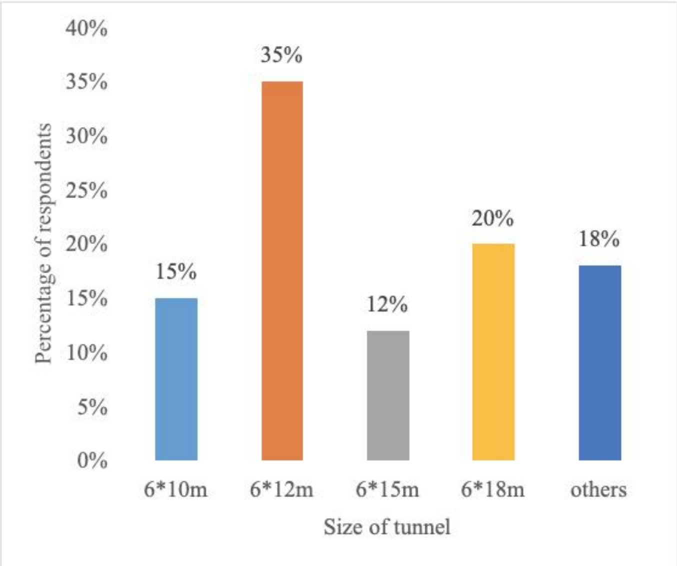

Figure 4 Size of the plastic tunnel used by the respondents

3.3 Vegetable production practices

3.3.1 Major vegetables grown by respondents

Tomato was the dominant vegetable cultivated under tunnels, grown by 70% of respondents. Beside tomato, other vegetables grown in the field were cauliflower, cabbage, leafy greens, cucumber, others (peas, beans, chilli, eggplants) which holds 8%, 4%, 6%, 10%, 2% respectively. The dominance of tomato shows its commercial importance and suitability for protected cultivation. According to MoALD (2024), tomato is among the major commercial vegetable crops cultivated in Nepal.

The most recent district level statistics (2022/23) indicate that Nuwakot has approximately 3049 ha, 39741Mt and 13034 kg/ha of total area, production, and productivity of vegetables respectively and the major vegetables grown in Nuwakot district are radish, cabbage, cauliflower, pumpkin, broad leaf mustard, cucumber, peas etc (Pokhrel et al., 2022).

3.3.2 Major varieties of vegetable crops grown for commercial farming

The major varieties of tomato were Sirjana and Sarbashrestha. They were the highest yielding varieties as per the farmers with a maximum reported yield of around 120 t/ha for Sirjana, and around 70 t/ha for Sarbashrestha (Table 2). White Top was most common variety of cauliflower. The variety of cabbage planted was Green Coronet, while Bhaktapur Local was the major variety of cucumber.

3.3.3 Types of seed used by the respondents

The majority of the respondent 60% people used hybrid seeds, (such as Sirjana and Sarbashrestha, for tomato, White Top, Snow Grace for cauliflower, Green Coronet, Futoski F1, for cabbage and Madhu F1, for cucumber). 10% of the respondents used local seeds (such as Kathmandu Local for cauliflower, and Bhaktapur Local for cucumber). While 18% used both local and hybrid seeds, and 12% of them used improved seeds (such as

Snowball 16 and Khumal Jyapu for cauliflower, Wonder Ball for cabbage). They received those seeds from agro vets, agro farm, retail shop and neighbours.

Table 2 Major varieties of vegetable grown

Vegetables	Varieties	Reported yield (t/ha)	Planting time	Harvesting time
Tomato	Srijana, Sarbashrestha	70-120	Feb-Mar (spring crop) Sept-Oct (autumn crop)	May-July (spring) Dec-Feb (autumn)
Cauliflower	White Top	30-35	Sept-Oct	Dec-Jan
Cabbage	Green Coronet	45-60	Sept-Oct	Dec-Feb
Cucumber	Bhaktapur local	25-35	Feb-Mar (spring) Aug-Sept (autumn)	Apr-Jun (spring) Oct-Nov (autumn)

3.3.4 Irrigation system and mulching practices

From the study area, it was found that, the majority of the respondents i.e. 55% of them used drip irrigation system and 22% of the respondents used furrow irrigation system by channel for irrigation. 16% of the respondents used sprinkler irrigation and 7% of them used flooding system by pipe line for irrigation. Farmers flood their land through pipelines which supply the irrigation water from river, pond.

Mulching was practiced by 70% of farmers, while the remaining 30% said they didn't (Figure 5; Figure 6). Straw, hay, tree leaves were some of the common materials used as organic mulch, while plastic mulch was a common material for non-organic mulching.

Drip irrigation and mulching are common in protected vegetable cultivation because they maintain soil growth, controls weed growth and improve water use efficiency (Parte et al., 2022).

Figure 5 Drip irrigation with mulching in tomato

Figure 6 Drip irrigation without mulching in tomato

3.3.5 Nutrients sources

The majority of the farmers i.e. 58% used FYM and chemical fertilizer such as Urea, Diammonium Phosphate (DAP), Muriate of Potash (MOP) as a nutrient source for vegetable farming, 18% of the respondent used FYM in integration with poultry manure and chemical fertilizer, 16% of the respondent used FYM with goat manure and chemical fertilizer as a nutrient source for vegetable farming and 8% of the respondent used organic manure only. According to Dahal and Manandhar (2021), farmers commonly combine FYM and poultry manure with chemical fertilizers to enhance crop productivity. However, declining availability of FYM due to reduced livestock rearing has increased farmers' reliance on chemical inputs to maintain soil fertility and high yields.

3.4 Marketing of vegetables

3.4.1 Means of vegetable product selling

The marketing of vegetables involves different actors and paths based on farmer's market access, production volume, and market connections. The farmers in the survey area apply both direct and indirect methods to market their products. Majority of farmers relied on middlemen because of the convenience of collection, transportation support, and better access to larger markets.

Of the respondents, 55% of them sold their vegetable product through middlemen, making it the most common marketing method. 30% of the vegetable products were sold through co-operatives. And the remaining 15% of the vegetable products were sold by themselves to local markets or to direct consumers. The results show that while certain farmers access markets directly, numerous farmers relies on third person to sell their products.

3.4.2 Marketing channel

The marketing channel involved multiple stakeholders including farmers, cooperatives, traders, wholesalers, and consumers. The diversity provided farmers with various options for selling their products based on their production capacity and market access. Some farmers sold their products directly to the local markets and consumers, while others marketed their vegetables through cooperatives, which is then supplied to wholesalers and urban markets like Kathmandu. A considerable number of farmers also depend on middlemen, who collected vegetables from farms and supplied them to wholesalers and urban consumers. In some cases, farmers sold their produced to contract buyers or companies. These channels indicate that vegetable marketing in the study area includes both direct and intermediary based systems, with cooperatives and middleman playing important roles in connecting rural producers with urban markets.

The following mentioned are the four marketing channels they used:

(1) Direct marketing channel

Farmers → Local Markets → Consumers

Some farmers sold their vegetables directly in nearby local markets. This helped farmers to directly communicate with consumers and retain control over the selling process.

(2) Cooperative-based marketing channel

Farmers → Cooperatives → Wholesalers → Urban Markets (Kathmandu) → Consumers

Through the cooperatives, farmers collectively marketed their produced and accessed larger markets. Cooperatives acted as a connecting bridge between producers and wholesalers, and helped farmers in collecting and transportation of fresh produced.

(3) Middlemen based marketing channel

Farmers → Middlemen → Wholesalers → Urban Markets → Consumers

This was the most common way of marketing in the study area. Middlemen collected vegetables from farmers and supplied them to wholesalers and urban markets.

(4) Contract based marketing channel

Farmers → Contract Buyers/Companies → Consumers

Farmers occasionally sold vegetables through contract buyers or companies where buyers directly collected produced from farms based on prior agreements.

3.5 Annual income by vegetable farming under plastic tunnel

The annual reported income from protected vegetable farming varied among farmers. About 38% of farmers reported earnings of more than NRs. 3 lakhs annually, 24% had an annual income between 2-3 lakhs, 21% earned NRs. 1-2 lakhs, and 17% earned less than NRs. 1 lakh (Figure 7). The findings indicate that tunnel vegetable farming has become an important source of cash income for farmers of Meghang Rural Municipality.

Finding of the study was in coincides with Bhandari and Paudel (2021), who reported that the lowest proportion of farmers earned less than one lakh annually from vegetable farming while assessing farmers' income from vegetable production. The study of vegetable farmer's livelihood in Kathmandu valley by Rai et al. (2019) also found the minimum earning of the vegetable farming ranging from NRs. 50,000 to 500,000.

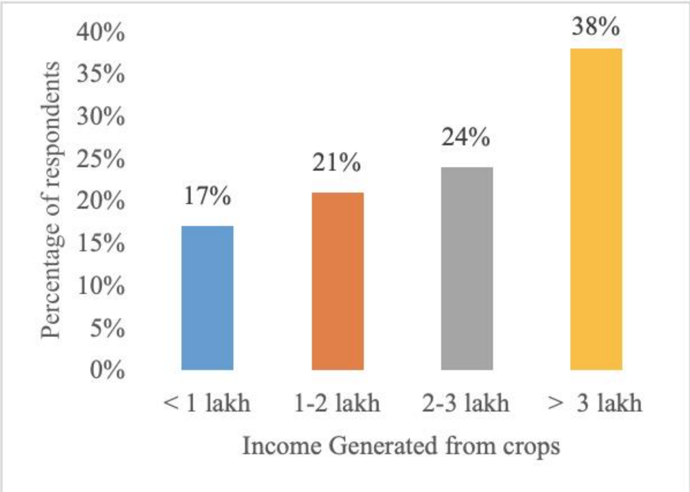

Figure 7 Annual income by vegetable farming under plastic tunnel

3.6 Income expenditure by respondents

The income from the farming was wisely utilized in different aspect of life. 15% of the earnings was allocated towards food stuffs (Figure 8). Likewise, a significant portion i.e. 21% of the income was dedicated to education, while 14% was used for healthcare purposes. 8% of earning was used in clothing, 23% was used as savings and the remaining 19% was used in other expenses such as buying agriculture inputs, travel and entertainment.

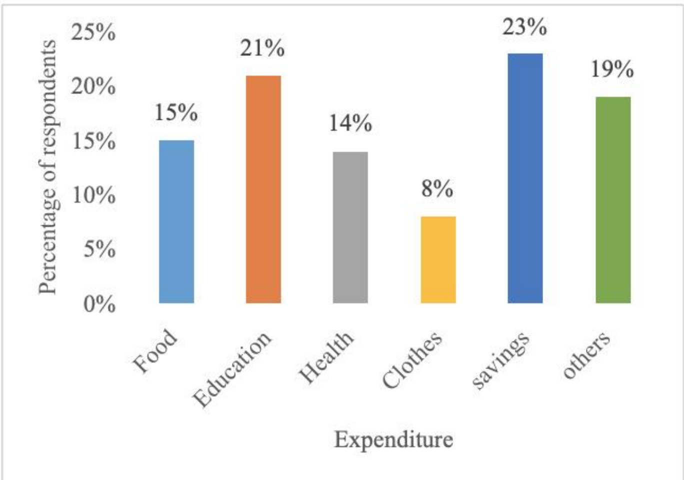

Figure 8 Income expenditure by respondents

According to Bhandari and Paudel (2021) majority of farmers spend their revenue on necessities like food, clothing, and school supplies, as typical areas of spending. As they made more money, they either saved it or used it for other purposes, such as buying farmland, renovating homes, constructing restrooms, and other lavish items.

3.7 Reasons for practicing tunnel farming and challenges faced by respondents

Farmers in the research area are encouraged to adopt tunnel cultivation because vegetable produced under tunnel gives higher yield, better quality, off-season prices, better climate adaptability, and better disaster protection compared to open field. The cool temperate climate of the elevated area, where low temperatures and weather fluctuations frequently limit open field vegetable cultivation, the implementation of this technology provides farmers with safer environment for their vegetables. Plastic tunnels provides protective microclimate that enables more stable and reliable production compared to open field conditions. The protective role of tunnels against unfavourable weather conditions like intense rainfall, hailstorm, high winds and frost motivates farmers to adopt this system. This lowers the chance of crop damage and production loss. Moreover, tunnel farming enables off-season vegetable cultivation which gives farmers access to market when supply from open field is limited. This seasonal benefit leads to increase market prices, as vegetables grown in tunnels are typically of superior quality and accessible during times of shortage. Thus, the integration of favourable climatic conditions, enhanced crop protection and off season cultivation with superior quality products leads to more profitable and resilient production system compared to open cultivation in the study area.

Although plastic tunnel vegetable cultivation has income increasing potential, it is still constrained by factors such as capital, markets, technology, and agricultural inputs. One of the major constraints is the high initial investment for the construction of tunnel structures including the cost of plastic sheets, pipes, and labour, which restricted farmers from adoption and expansion. Moreover, limited access to the market and dependence on middlemen reduces bargaining power and results in lower farm gate price despite higher production costs. Insufficient training and extension support further limits the production capacity, as farmers have minimal knowledge about modern farming techniques, pest and disease control, and efficient use of resources, all of which are essential for maximizing tunnel productivity. In addition, irregular availability and limited access to quality agricultural inputs like seeds, fertilizers and organic manure create additional production uncertainties and impact yield. These constraints demonstrate that although plastic tunnel farming has considerable income generating potential, its effectiveness is greatly affected by financial access, institutional support and input supply systems.

4 Discussion

4.1 socio-economic factors influencing tunnel vegetable farming

The findings show that the adoption of tunnel technology is highly influenced by socioeconomic characteristics and farmer’s motivation to improve their household earnings. Agriculture being a primary occupation and the dominance of economically active farmers indicates that protected vegetable cultivation has been an important commercial enterprise for people of Meghang. The farmers who are active and have received basic education are more interested in adopting improved technologies because they are better able to understand technical information, participate in extension programs, respond to market opportunities and manage labor intensive work. Likewise, farmers having larger landholdings can allocate more land for commercial vegetable farming and recover higher investment costs associated with tunnel constructions. Although women also participate in farming activities, men have more decision making power, from managing marketing channels to investment decisions, while women are more active in production activities.

These results align with earlier research carried out in Nepal. Kc et al. (2021) found that tunnel technology enhanced production consistency and livelihood prospects for smallholder farmers by reducing climatic constraints. Likewise, Gc and Hall (2020) found that commercialization of smallholder farming is influenced by better access to enhanced production technologies and market prospects. More recently, Subedi et al. (2023) have highlighted that education, extension services, farming experiences and government subsidies significantly influence farmers to adopt protected cultivation, emphasizing that farmers are likely to invest in protected vegetable farming with a solid technical and institutional support.

In general, the findings indicate that the growth and expansion of protected farming relies not only on economic capacity of a farmer but also on their access to extension services, technical education and affordable financial support. Strengthening these support systems might encourage wider adoption of tunnel technology, boost agricultural productivity, and improve the quality of life for smallholder farming households.

4.2 Technical features and agronomic implications of plastic tunnel cultivation

The production practices observed during the survey suggest that farmers are more interested in protected farming with modern and improved cultivation practices including use of hybrid seeds, drip irrigation, mulching practices, and integrated nutrient management. Medium sized tunnel dominated the field as they require lower initial investments compared to high tunnels, and they provide sufficient space for intercultural operations such as training and pruning, skating, irrigation and harvesting. Likewise, the farmers of Meghang have mostly used 90 GSM plastic sheets with 6*12 m tunnel dimension, which is due to their suitability, affordability, durability and ease availability. As farmers seek cost effective structures, for their fragmented lands and to withstand climatic conditions, 90 GSM sheets with 6*12 m dimension tunnels happen to be the best choice for farmers (Lamichhane et al., 2023).

Observing the cultivation practices followed by farmers, it shows that, farmers are widely adopting climate smart practices to improve production. The use of drip irrigation helps provide direct water to the crop root zone which reduces water loss through evaporation and improves water use efficiency, while the use of plastic mulch preserves soil moisture, suppresses weed growth, regulates soil temperature, and reduces nutrient losses. The application of organic manure and chemical fertilizers together improves soil structure and ensure adequate supply of nutrients to plants for continuous crop growth and productivity. Similar benefits of integrating protected cultivation, efficient nutrient and irrigation management for sustainable farming have been reported in Nepal by Paudel et al. (2020) and Lamichhane et al. (2023). The adoption and practice of these new technologies indicates a gradual transition from conventional farming towards modern climate resilient vegetable farming.

However, for long term success and profitable business, farmers should take consideration on both the tunnel structures and proper agronomic practices. With technical and extension support and proper farming practices, the business would be profitable.

4.3 Crop choice, tomato dominance and production risk

Tomato is the dominant crop as seen in the study area, it is likely because of its high market demand, relatively higher economic returns and suitability for protected cultivation. Production under plastic tunnel provides favorable microclimate for off-season periods when open field cultivation is limited and market prices are generally higher. This helps farmers to extend production season, improve quality and access more profitable market.

These findings are consistent with recent studies on protected farming in Nepal. A study done by Subedi et al. (2023) shows that tomato is one of the most profitable crop grown under protected structures because of its high yielding potential and better market price compared to other vegetables. Similarly, Lamichhane et al. (2023) reported that tomato is the identified as the principal crop cultivated under protected structures in Nepal, highlighting its economic importance and its ability to adapt under protected structures. These studies suggest that, farmers prefer to invest in tomato for better financial returns despite high management cost.

However, reliance on one main cash crop may create a risk for farmers. Growing tomatoes in protected structures need regular care. If diseases break out or market price falls when the harvest coincide with many farmers, they will lose money. That is why, growing different crops is important. Crop diversification helps to protect against market volatility, reduces the spread of pests and improves soil health, to create more stable and sustainable protected farming in Nepal.

4.4 contribution of tunnel farming to income and Livelihood improvement

The findings show that vegetable farming under plastic tunnels has become an important source of cash income in households of Meghang Rural Municipality. The income is carefully utilized by farmers in different aspect of daily life such as food, education, healthcare, savings and reinvestment in agriculture outputs. This shows that, tunnel farming not only generates farm income but also strengthened different dimensions of rural Livelihood by improving household income and financial stability.

These findings are consistent with a recent study in Nepal. Kc et al. (2021) reported that the adoption of tunnel technology increased production opportunities, with higher farm income and employment and improved livelihoods. Similarly, Subedi et al. (2023) reported that protected vegetable farming was economically profitable with better financial returns compared to conventional production systems, although profitability depends on production cost, crop choices, market access and farm management. Likewise, Sapkota et al. (2022) reported that farmers viewed protected vegetable farming as a viable method for boosting household income and enhancing economic stability, despite challenges related to input costs and marketing.

However, the current study relies on a cross-sectional survey and descriptive analysis. Thus, the observed results related to livelihood should be seen as association rather than direct causal relationship with tunnel farming. Further research should be done including longitudinal data, before and after comparison, and economic evaluations to provide stronger evidence of long term contribution of protected farming in livelihood improvement. Finally, having easy access to quality inputs, urban markets, and technical knowledge and extension support will bring more profit to business and a happier livelihood to rural peoples.

4.5 Market dependency, institutional support and policy implications

In Meghang Rural Municipality, farmers relied on middlemen and cooperatives to market their vegetables rather than selling directly to the consumers. The dependency on intermediaries is likely due to limited access to urban markets, inadequate transportation facilities, small production volumes and the convenience of selling products via middlemen. Though middlemen provide an access to market, farmers often have limited bargaining power and receive lower farm gate prices.

These findings are consistent with previous studies in Nepal. Subedi et al. (2023) indicate that while protected vegetable farming is lucrative, insufficient market access, price fluctuations, and weak institutional support remain major constraints to its sustainability. Likewise, Sapkota et al. (2022) identified marketing difficulties, high transportation expenses, and reliance on middlemen as common challenges encountered by protected vegetables growers. Lamichhane et al. (2023) further highlighted that strengthening cooperatives, advancing extension services, and developing market infrastructure are crucial for promoting the adoption and long term success of protected cultivation in Nepal.

The current results indicate that improving market systems is equally important as advancing production technologies. Strengthening farmer cooperatives, encouraging collective marketing, improving market information services, and investing in rural transport and storage facilities could boost farmers bargaining power and improve the profitability of protected vegetable farming. Such institutional backing would contribute to more resilient vegetable value chains and improve the livelihoods of smallholder farming households.

4.6 Study limitations and future research needs

This study provides valuable insights into the role of plastic tunnel vegetable farming in income generation and livelihood improvement among farmers in Meghang Rural Municipality. However, certain constraints should be acknowledged. The study was based on a cross sectional survey of 100 farming households from a single rural municipality, potentially restricting the applicability of the results to the other agro ecological areas in Nepal. Moreover, the analysis relied primarily on farmers self-reported information on production and income, which may be recall bias and seasonal variations.

Despite these limitations, the study contributes to the increasing evidence about vegetable farming under protection in Nepal by offering household level information from an important vegetable producing area. In line with the suggestions of Lamichhane et al. (2023), future research should evaluate the long term economic, environmental, and climate resilience benefits of protected cultivation across different production systems and agro ecological zones. Comparative analysis of vegetable farming in plastic tunnels versus open fields, along with cost-benefit and value chain analysis would provide stronger evidence to support policy formulation and investment decisions. Such research would enhance understanding of how protected cultivation can contribute to sustainable agricultural commercialization and improved rural livelihoods in Nepal.

5 Conclusion and Prospects

The study assessed the role of plastic tunnel vegetable farming in household income generation and livelihood enhancement among farmers in Meghang Rural Municipality, Nuwakot. Plastic tunnels provide a favourable environment for crops to grow even in off-seasons with better quality and fetch high market prices. The findings suggest that tunnel-based vegetable farming is associated with higher reported income and perceived livelihood improvement among surveyed farmers.

The major findings from the survey are, tomato is the dominant crop grown inside tunnels with Sirjana being the major variety, most of the farmers use medium sized 6*12-dimension plastic tunnels, while 90 GSM plastic sheets are commonly in use. Most farmers practice drip irrigation and mulching to control weeds and maintain soil health. The products are mostly sold via middlemen or cooperatives, with a reported annual income of < 1 lakh to > 3 lakh depending on scale of farming. The income contributed to household expenditure such as food, education, healthcare and agricultural inputs, and savings. Overall, Plastic tunnels helped farmers overcome seasonal production limitations, produce them during times when open field cultivation is quite challenging and continuing the supply of vegetables in off-seasons to fetch higher market prices.

However, farming in Meghang Rural Municipality is affected by several challenges. Firstly, farmers expressed significant concerns regarding high initial cost for tunnel constructions which limits smallholder’s ability to expand production. Secondly, access to quality inputs like seeds, fertilizers, organic manure, and other inputs remains unstable. Moreover, insufficient technical trainings and extension services affect pest and disease management and resource use efficiency. In addition, the lack of organized markets leads many farmers to rely on middlemen, weakening their bargaining power. Due to these obstacles in farming, smallholder farmers may not fully benefit from protected cultivation.

The future progress of tunnel based vegetable farming in the study area requires strengthening collaboration among local governments, cooperatives, financial institution, agriculture extension departments, and farmers to establish more stable mechanism for input supply, technical training, low-interest loans, and market linkages. Cooperative marketing, product grading and packaging, collective transportation, and connections with urban markets should also be emphasized to reduce dependence on middlemen and improve farmers’ bargaining power.

Further studies should include larger sample sizes, cost benefit analysis, net income calculations, input-output ratios, and comparative studies of tunnel versus open field farming systems. This would help address the limitations of the present study which is based only on descriptive cross-sectional data and would also enhance the academic rigor of the paper.

Author’s contributions

Aayushma Poudel conceptualized and designed the study, led the field work, performed the data analysis and prepared the manuscript. Krish Rauniyar helped in editing, data validation and manuscript revision. Chandani Begam and Asmita Oli assisted in field work, data collection and analysis. Bishnu Prasad Bhattarai supervised the data collection and contributed to data analysis and interpretation. All authors read and approved the final manuscript.

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Research Report Open Access

Evaluation of Fruit Characteristics of Major Varieties of Litchi in Sarlahi, Nepal

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Abstract Litchi (*Litchi chinensis* Sonn.) is an economically important subtropical fruit crop widely cultivated in the Terai region of Nepal. This study evaluated the fruit morphological and quality characteristics of seven major litchi cultivars (Shahi, China, Seedless, Early Large Red, Calcuttia, Muzaffarpur, and Bombai) grown at the Tropical Horticulture Center, Sarlahi, Nepal, during the 2024 fruiting season. The experiment was conducted using a Randomized Complete Block Design (RCBD) with four replications. Fruit morphology, physical characteristics, seed traits, and total soluble solids (TSS) were assessed using standard pomological methods. Significant differences were observed among cultivars for most evaluated traits. Seedless exhibited superior commercial attributes, characterized by larger fruits, higher aril proportion, and smaller seeds, indicating a greater edible portion and enhanced market potential. In contrast, Shahi recorded the highest total soluble solids, reflecting superior sweetness and eating quality. Considerable variation was also observed in fruit colour, shape, seed morphology, and other physical characteristics, demonstrating substantial genetic diversity among the evaluated cultivars. Overall, the findings indicate that Seedless is the most promising cultivar for commercial production because of its desirable fruit quality traits, while Shahi is particularly suitable for fresh consumption owing to its superior sweetness. These results provide valuable information for cultivar selection, orchard management, and future litchi improvement programmes in Nepal.

Keywords Litchi (*Litchi chinensis* Sonn.); Fruit quality; Pomology; Cultivar evaluation; Total soluble solids

1 Introduction

Litchi (*Litchi chinensis* Sonn.) is one of the most important subtropical fruit crops cultivated worldwide for its attractive appearance, pleasant aroma, excellent flavor, and high nutritional value. The fruit is rich in sugars, vitamin C, phenolic compounds, and antioxidants, making it highly valued for both fresh consumption and processing. South and Southeast Asia account for a major proportion of global litchi production, with Nepal being one of the important producing countries in the Himalayan region. In Nepal, litchi is predominantly cultivated in the Terai belt, where favorable climatic conditions support its commercial production. According to the Ministry of Agriculture and Livestock Development (MoALD, 2023), litchi occupies approximately 5,769 ha, with an annual production of 42,736 metric tons and an average productivity of 7.41 t/ha. Among the major production districts, Sarlahi has emerged as an important litchi-growing area because of its subtropical climate, fertile alluvial soils, and increasing commercial orchards, contributing substantially to local livelihoods and the regional fruit economy.

The commercial value of litchi is largely determined by fruit quality attributes rather than yield alone. Consumers generally prefer fruits with larger size, higher fruit weight, greater edible aril proportion, smaller seeds, attractive peel color, and higher total soluble solids (TSS), as these characteristics directly influence market acceptability, consumer preference, shelf value, and profitability (Menzel, 2005). Small-seeded or "chicken-tongue" seed cultivars are particularly desirable because they possess a greater edible portion and fetch premium market prices (Singh et al., 2012). Likewise, TSS is one of the most important quality indicators because it reflects sugar accumulation and sweetness, thereby influencing fruit taste and overall eating quality (Hussain et al., 2021). Therefore, systematic evaluation of fruit morphological and quality traits is essential for identifying superior cultivars suitable for commercial cultivation, breeding programs, and orchard improvement.

Fruit characteristics in litchi are strongly influenced by cultivar genetics and their interaction with environmental conditions. Previous studies have documented considerable variation among cultivars in fruit size, fruit weight, seed morphology, aril development, and physicochemical quality (Nacif et al., 2001; Singh et al., 2012; Wang et al., 2017; Nath et al., 2022). Similarly, Chaudhary et al. (2023) evaluated major litchi cultivars in the central Terai of Nepal and reported significant differences in several fruit quality traits, highlighting the importance of cultivar selection for commercial production. However, most published studies have focused on general varietal descriptions or evaluations conducted under different agroecological conditions. Because fruit quality is influenced by both genetic background and environmental factors, cultivar performance may vary considerably across production regions. Consequently, findings from other countries or even other regions of Nepal cannot be directly extrapolated to the orchards of Sarlahi.

Sarlahi represents one of Nepal's important commercial litchi-producing districts, yet comprehensive comparative information on the fruit morphological and quality characteristics of its major cultivated varieties remains limited. Scientific evaluation under local agro-climatic conditions is necessary to identify cultivars with superior commercial traits, provide reliable recommendations to growers, and support evidence-based orchard management. Furthermore, understanding varietal differences in fruit quality can assist breeding programs, improve cultivar selection, and enhance the competitiveness of Nepalese litchi in domestic and potential export markets.

Therefore, this study aimed to evaluate the differences in fruit morphological and quality characteristics among seven major litchi cultivars grown under the agro-climatic conditions of Sarlahi, Nepal. The study specifically compared fruit morphology, fruit size, fruit weight, pericarp weight, aril weight, seed characteristics, and total soluble solids (TSS) to identify superior cultivars with greater commercial potential. The findings are expected to provide valuable scientific information for cultivar selection, orchard management, future breeding programs, and the sustainable development of the litchi industry in Nepal.

2 Materials and Methods

2.1 Study site

The experiment was conducted during the 2024 fruiting season at the Tropical Horticulture Center (THC), Sarlahi District, Madhesh Province, Nepal (26.4703° N, 86.7325° E). The experimental site is located in the subtropical Terai region of Nepal at an altitude of approximately 85 m above sea level. The area experiences a humid subtropical climate characterized by hot summers, mild winters, and a distinct monsoon season. The average annual temperature ranges from 10 °C–38 °C, with an annual rainfall of approximately 1,400–1,800 mm, most of which occurs from June to September. The orchard soil is deep, well-drained alluvial loam with good fertility, which is considered suitable for commercial litchi production.

2.2 Plant materials and experimental design

Seven commercially important litchi (*Litchi chinensis* Sonn.) cultivars, namely Shahi, China, Seedless, Early Large Red (ELR), Calcuttia, Muzaffarpur, and Bombai, were selected for evaluation. The cultivars were maintained in the experimental orchard of the Tropical Horticulture Center, Sarlahi. Uniform, healthy, air-layered trees aged 15–20 years with comparable canopy size and vigor were selected for the study. The orchard was established under a square planting system with uniform spacing of 10 m × 10 m. Standard orchard management practices, including irrigation, fertilizer application, weed management, pruning, and plant protection measures, were uniformly followed throughout the experimental period to minimize management-related variation.

The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replications. Each tree represented one experimental unit, resulting in a total of 28 experimental trees (7 cultivars × 4 replications).

2.3 Fruit sampling

Fruits were harvested at commercial maturity based on uniform peel colour development, characteristic cultivar appearance, and market harvest stage. Twenty fruits were randomly collected from each experimental tree, representing all four canopy directions (north, south, east, and west) and different canopy heights to minimize sampling bias. Damaged, diseased, insect-infested, and malformed fruits were excluded from sampling. Immediately after harvest, the samples were transported to the laboratory for morphological and physical analyses.

2.4 Determination of fruit morphological characteristics

Fruit morphological characteristics, including fruit colour, fruit shape, fruit size, seed colour, seed shape, seed size, and aril colour, were recorded using freshly harvested mature fruits. Fruit maturity was identified based on characteristic peel colour and varietal appearance. Morphological descriptors were evaluated following the standard litchi descriptor guidelines described by Nacif et al. (2001) and Saikia and Kotoky (2022).

2.5 Determination of fruit physical characteristics

Fruit length, fruit width, fruit weight, pericarp weight, aril weight, seed length, seed width, and seed weight were determined using twenty representative fruits from each experimental unit. Fruit and seed length were measured from the base to the apex, while width was measured at the widest portion using a digital Vernier caliper with an accuracy of 0.01 cm. Fruit, pericarp, aril, and seed weights were measured using a calibrated digital electronic balance with an accuracy of 0.01 g.

Total soluble solids (TSS) were determined using freshly extracted juice obtained from the edible aril. The juice was filtered through muslin cloth and a few drops were placed on the prism of a hand-held digital refractometer (0–32 °Brix range). The instrument was calibrated with distilled water before each measurement, and TSS values were expressed as °Brix at room temperature. Three independent measurements were recorded for each experimental unit, and their average value was used for statistical analysis.

2.6 Statistical analysis

The collected data were entered into Microsoft Excel and analyzed using R software version 4.4.0. Analysis of variance (ANOVA) was performed to determine the significance of differences among cultivars. Mean separation was carried out using Duncan's Multiple Range Test (DMRT) at the 5% level of significance ($p \leq 0.05$). Coefficient of variation (CV%) and overall treatment means were also calculated to assess experimental variability and trait performance.

3 Results and Analysis

3.1 Fruit morphology of tested varieties

Significant variation was observed in fruit morphological characteristics among the seven evaluated litchi cultivars (Table 1). Fruit colour varied from red, crimson red, pinkish red, and tyrian rose to brownish-green. Likewise, fruit shape ranged from oval and cordate to conical, oblong, and globose, while fruit size was classified as medium or large depending on the cultivar. Seedless, Calcuttia, and Muzaffarpur produced comparatively larger fruits, whereas Shahi, China, Early Large Red (ELR), and Bombai produced medium-sized fruits.

Table 1 Morphological characteristics of fruit among seven litchi (*Litchi chinensis* Sonn.) varieties evaluated in Sarlahi, Nepal

Varieties	Fruit color	Fruit shape	Fruit size
Shahi	Red	Oval	Medium
China	Tyrian rose	Cordate	Medium
Seedless	Brownish with greenish	Heart or globose	Large
ELR	Crimson red	Oval	Medium
Calcutta	Pinkish red	Oblong or lopsided	Large
Muzaffarpur	Crimson red	Conical	Large
Bombai	Red	Oval	Medium

3.2 Seed morphology of tested varieties

Considerable variation was also observed in seed morphology among the studied cultivars (Table 2). Seed colour ranged from light brown to dark chocolate, whereas seed shape varied between elliptic oblong and elliptic oval. Seedless was the only cultivar possessing small seeds, while Calcuttia and Muzaffarpur had large seeds.

Differences were also recorded in aril colour, varying from grayish white and creamy white to dirty creamy white among the evaluated cultivars.

Table 2 Seed morphological characteristics of seven litchi (*Litchi chinensis* Sonn.) cultivars evaluated in Sarlahi, Nepal

Varieties	Seed color	Seed shape	Seed size	Aril color
Shahi	Dark chocolate	Elliptic oblong	Medium	Grayish white
China	Light brown	Oblong medium	Creamy	White
Seedless	Dirty chocolate	Elliptic oval	Small	Creamy
Early Large Red	Light brown	Elliptic oblong	Medium	Grayish
Calcuttia	Dark chocolate	Elliptic oblong	Large	Dirty creamy white
Muzaffarpur	Dark chocolate	Elliptic oblong	Large	Creamy
Bombai	Light brown	Elliptic oblong	Medium	Creamy

3.3 Fruit length, fruit width and fruit weight

Fruit length, fruit width, and fruit weight differed significantly among the evaluated cultivars (Table 3). Fruit length ranged from 3.25 to 3.64 cm. Early Large Red recorded the greatest fruit length (3.64 cm), which was statistically comparable with China (3.61 cm) and Muzaffarpur (3.60 cm), whereas Bombai produced the shortest fruits (3.25 cm).

Fruit width varied significantly from 2.90 to 3.30 cm. China exhibited the highest fruit width (3.30 cm), followed by Bombai (3.17 cm) and Seedless (3.16 cm), while Shahi recorded the lowest value (2.90 cm).

Fruit weight also differed significantly among cultivars, ranging from 18.85 to 23.10 g. Seedless produced the heaviest fruits (23.10 g), followed by China (21.96 g), whereas Shahi recorded the lowest fruit weight (18.85 g).

Table 3 Fruit length, fruit width, and fruit weight of seven litchi (*Litchi chinensis* Sonn.) cultivars evaluated in Sarlahi, Nepal

Varieties	Fruit length (cm)	Fruit width (cm)	Fruit weight (g)
Shahi	3.42^{ab}	2.90^{c}	18.85^{c}
China	3.61^{a}	3.30^{a}	21.96^{ab}
Seedless	3.44^{ab}	3.16^{ab}	23.10^{a}
Early Large Red	3.64^{a}	3.02^{bc}	19.85^{bc}
Calcuttia	$3.44a^{b}$	3.09^{bc}	20.73^{abc}
Muzaffarpur	3.60^{a}	2.95^{c}	19.20^{c}
Bombai	3.25^{b}	3.17^{ab}	19.71^{bc}
f-probability	*	**	*
CV%	4.3	3.8	8.2
Grand Mean	3.49	3.08	20.49

Note: *, **, *** represent significance at 5%, 1% and 0.1% respectively. Means followed by the same letter within a column are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$

3.4 Pericarp weight, aril weight, seed length, seed width and seed weight

Pericarp weight, aril weight, seed length, seed width, seed weight, and total soluble solids (TSS) differed significantly among the evaluated cultivars (Table 4).

Pericarp weight ranged from 1.38 to 3.58 g. Muzaffarpur recorded the highest pericarp weight (3.58 g), followed by Bombai (2.68 g), whereas Shahi exhibited the lowest value (1.38 g).

Aril weight ranged from 10.72 to 15.14 g. Seedless produced the highest aril weight (15.14 g), followed by Calcuttia (13.24 g) and China (13.17 g), whereas Muzaffarpur recorded the lowest aril weight (10.72 g).

Significant differences were also observed in seed dimensions. Muzaffarpur produced the longest seeds (2.79 cm), while Seedless recorded the shortest seed length (1.85 cm). Seed width ranged from 1.04 to 1.70 cm, with Bombai producing the widest seeds (1.70 cm) and Seedless the narrowest (1.04 cm). Seed weight varied between 1.20 and 4.29 g. China produced the heaviest seeds (4.29 g), whereas Seedless had the lightest seeds (1.20 g).

Total soluble solids ranged from 18.25 to 21.50 °Brix. Shahi recorded the highest TSS (21.50 °Brix), followed by China (19.75 °Brix), whereas Early Large Red and Calcuttia exhibited the lowest values (18.25 °Brix).

Table 4 Pericarp weight, aril weight, seed dimensions, seed weight, and total soluble solids (TSS) of seven litchi (*Litchi chinensis* Sonn.) cultivars evaluated in Sarlahi, Nepal

Varieties	Pericarp weight (g)	Aril weight (g)	Seed length (cm)	Seed width (cm)	Seed weight (g)	TSS (°Brix)
Shahi	1.38^{d}	11.40^{b}	2.38^{b}	1.62^{a}	3.82^{ab}	21.50^{a}
China	1.79^{cd}	13.17^{ab}	2.40^{b}	1.67^{a}	4.29^{a}	19.75^{b}
Seedless	1.86^{c}	15.14^{a}	1.85^{c}	1.04^{b}	1.2^{c}	18.75^{bc}
Early Large Red	1.68^{cd}	12.04^{b}	2.37^{b}	1.51^{a}	3.36^{b}	18.25^{c}
Calcuutia	2.57^{b}	13.24^{ab}	2.28^{b}	1.49^{a}	3.27^{b}	18.25^{bc}
Muzaffarpur	3.58^{a}	10.72^{b}	2.79^{a}	1.48^{a}	3.63^{ab}	19.25^{bc}
Bombai	2.68^{b}	12.56^{ab}	2.38^{b}	1.70^{a}	4.04^{ab}	19.25^{bc}
f-probability	***	*	***	**	***	**
CV%	13	13	6.9	12.3	16.5	4.7
Grand Mean	2.22	12.61	2.34	1.5	3.37	19.28

Note: *, **, *** represent significance at 5%, 1% and 0.1% respectively. Means followed by the same letter within a column are not significantly different according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$

4 Discussion

The present study demonstrated significant variation in fruit morphological and quality characteristics among the seven evaluated litchi cultivars, indicating that fruit traits are largely governed by genetic differences among cultivars and their interaction with the growing environment. Fruit morphology, including colour, shape, and size, varied considerably across cultivars, reflecting differences in genetic makeup that determine fruit development and external appearance. Environmental factors such as temperature, solar radiation, soil fertility, and orchard management may further influence the expression of these traits, although cultivar genetics remain the primary determinant. Similar variation in fruit morphology among commercial litchi cultivars has been reported by Nacif et al. (2001) and Nath et al. (2022), who concluded that fruit appearance is predominantly cultivar dependent.

Significant differences were also observed in fruit length, fruit width, and fruit weight among the evaluated cultivars. Seedless produced the highest fruit weight, whereas Early Large Red and China recorded superior fruit dimensions. Fruit size is a complex quantitative trait regulated by cell division and cell expansion during fruit development and is influenced by the availability of carbohydrates and assimilates during the fruit growth period. Cultivars possessing greater sink strength generally accumulate more assimilates, resulting in larger and heavier fruits. Comparable variation in fruit size among litchi cultivars has been documented by Wang et al. (2017) and Chaudhary et al. (2023). Minor differences between the present findings and previous reports may be attributed to variations in environmental conditions, orchard management practices, tree age, and regional agroecological characteristics.

Seed characteristics showed marked differences among cultivars, with Seedless exhibiting significantly smaller and lighter seeds than the remaining cultivars. Small-seeded cultivars are highly desirable because reduced seed size increases the proportion of edible aril, thereby improving consumer acceptance and market value. The larger aril weight recorded in Seedless further supports this relationship, indicating that suppression of seed development allows greater allocation of assimilates toward aril growth. Similar observations have been reported by Singh et al. (2012), who described "chicken-tongue" seeded cultivars as commercially superior because of their higher edible portion. Nath et al. (2022) also emphasized that seed morphology is genetically controlled and serves as an important criterion in cultivar selection and breeding programmes.

Total soluble solids (TSS), an important indicator of fruit sweetness and eating quality, differed significantly among cultivars. Shahi recorded the highest TSS, suggesting superior sugar accumulation during fruit maturation. The accumulation of soluble sugars in litchi fruit is regulated by genotype and influenced by physiological processes such as carbohydrate translocation, photosynthetic efficiency, enzyme activity, and fruit maturity at harvest. Climatic conditions during fruit development, particularly temperature and light intensity, may further influence sugar accumulation. Hussain et al. (2021) similarly reported that cultivar genetics play a dominant role in determining soluble solids, while environmental conditions modify the extent of sugar accumulation. The relatively high TSS of Shahi indicates its suitability for fresh consumption and premium fruit markets.

The observed varietal differences have important implications for commercial litchi production in Nepal. Seedless combined high fruit weight, greater aril weight, and reduced seed size, making it an attractive cultivar for consumers and the fresh fruit market. In contrast, Shahi exhibited superior sweetness, while China and Early Large Red performed well for fruit size. These findings suggest that cultivar selection should be based on the intended market, with Seedless being preferable where edible portion is prioritized and Shahi being suitable where sweetness is the primary quality attribute. Region-specific evaluation of cultivars is essential because fruit quality is influenced by genotype × environment interactions, and cultivar performance may vary under different agro-climatic conditions (Menzel, 2002).

Although the present study provides valuable baseline information on the fruit quality characteristics of major litchi cultivars grown in Sarlahi, it was conducted at a single location during one fruiting season. Consequently, seasonal variation and environmental effects could not be fully evaluated. Future studies should include multi-location and multi-year trials to assess the stability of cultivar performance under diverse agroecological conditions. In addition, integrating physiological, biochemical, molecular, and postharvest quality analyses would provide a more comprehensive understanding of varietal performance and support the development of improved litchi cultivars for commercial production in Nepal.

5 Conclusion

This study demonstrated significant variation in fruit morphological and quality characteristics among seven major litchi (*Litchi chinensis* Sonn.) cultivars grown under the agro-climatic conditions of Sarlahi, Nepal. Among the evaluated cultivars, Seedless exhibited superior commercial attributes, including higher fruit weight, greater aril weight, and smaller seed size, indicating a higher edible portion and greater consumer preference. Shahi recorded the highest total soluble solids (TSS), reflecting superior sweetness and eating quality, whereas China and Early Large Red produced comparatively larger fruits. These findings confirm that cultivar selection plays a crucial role in determining fruit quality and market value.

The results provide valuable scientific information for growers, researchers, and orchard managers in selecting cultivars according to market demand and production objectives. Based on the overall evaluation of fruit quality traits, Seedless appears to be the most promising cultivar for commercial cultivation in the Terai region of Nepal, while Shahi is particularly suitable for fresh fruit markets where sweetness is a key quality attribute.

Since the present investigation was conducted at a single location during one fruiting season, further multi-location and multi-year evaluations are recommended to validate the stability of cultivar performance under diverse agroecological conditions. Future research should also integrate physiological, biochemical, molecular, and postharvest quality assessments to support breeding programmes and the sustainable development of the litchi industry in Nepal.

Authors' contributions

AA and AP were involved in conceptualization, conducting the experiment, data curation, editing, data analysis, writing the original draft, manuscript revision and providing the final structure to the manuscript. Both authors read and approved the final manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Feature Review Open Access

Effects of Organic Fertilization on Soil Health, Nutrient Uptake, and Fruit Quality of Grapevine

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Abstract Excessive or long-term reliance on chemical fertilizers in grape production can lead to declines in soil organic matter, nutrient imbalances, and weakened microbial functions, thereby constraining the sustainable development of vineyards. This study systematically examines the effects of organic fertilization on the "soil-grapevine-fruit" system, with particular emphasis on soil health, nutrient uptake, vine growth, yield, and fruit quality. The results indicate that organic fertilizers can increase soil organic matter and the availability of nutrients such as nitrogen, phosphorus, and potassium, improve soil porosity, aggregate stability, and water-holding capacity, and enhance microbial abundance and related enzyme activities. Appropriate substitution of chemical fertilizers with organic fertilizers can also promote root development and nutrient uptake, while increasing grape yield, the sugar–acid ratio, and the contents of vitamin C, phenolic compounds, and antioxidants. However, these effects vary depending on fertilizer type, substitution rate, soil conditions, grape cultivar, and climate. Overall, the combined application of organic and mineral fertilizers is more effective than either fertilization strategy alone, as it can maintain grape yield and fruit quality while improving soil ecological functions. These findings provide a theoretical basis for reducing chemical fertilizer inputs, improving fertilizer-use efficiency, and developing sustainable nutrient management strategies in vineyards.
Keywords Grapevine; Organic fertilization; Soil health; Nutrient uptake; Fruit quality; Sustainable production

1 Introduction

Grapevine is an important fruit crop worldwide, and berry composition directly influences the market value of table grapes and the quality of wine (Zhu et al., 2022; Kaya et al., 2024a). In grape cultivation, nutrient management is closely related not only to yield but also to vegetative growth and berry composition, thereby affecting the gap between actual and potential productivity (James et al., 2023). Soil chemical properties and vineyard management practices also influence the balance between vegetative and reproductive growth, which is essential for maintaining stable long-term production (Cataldo et al., 2021). Therefore, sustainable nutrient management has become a key strategy for simultaneously maintaining grape yield, fruit quality, ecosystem functions, and stress resilience (Cataldo et al., 2021; Zhu et al., 2022).

Long-term dependence on chemical fertilizers has also caused considerable agronomic and environmental problems. Excessive or imbalanced application of mineral fertilizers can alter vine vigor and fruit composition while reducing soil biological functions and the activities of enzymes involved in nutrient cycling (James et al., 2023; Visconti et al., 2024). Continuous application of inorganic fertilizers alone may also lead to declines in soil organic matter, soil acidification, nutrient imbalance, salinization, and environmental pollution (Bhatt et al., 2019; Wu et al., 2024). In vineyards, inappropriate management can similarly result in soil compaction, erosion, and biodiversity loss, ultimately reducing grape yield and quality (Cataldo et al., 2021; Kaya et al., 2025). Prolonged fertilization may also reshape soil microbial communities and reduce the abundance of beneficial microorganisms positively associated with grape productivity (Li et al., 2024; Visconti et al., 2024). Therefore, improving nutrient-use efficiency is more important than simply increasing fertilizer inputs.

Organic fertilization provides an alternative approach to improving the vineyard soil environment. Organic fertilizers can supply nutrients while increasing soil organic matter, improving soil structure, porosity, water-holding capacity, and nutrient-buffering capacity, and enhancing microbial abundance and soil enzyme activity (James et al., 2023; Visconti et al., 2024; Wu et al., 2024). Hazarika et al. (2024) established 14 combined treatments involving organic fertilizers and microbial inoculants. Among them, the treatment consisting of pig manure + Azospirillum + PSB + KSB + Trichoderma + CPP + BD500 + BD501 resulted in the highest levels of soil organic carbon, total carbon, total N, available N/P/K, Mn, Zn, and CEC, together with the greatest populations of bacteria and actinomycetes and the highest concentrations of Mn, Zn, and chlorophyll in grape leaves. Mairata et al. (2024) further reported that organic mulches can improve nutrient-poor semiarid soils and enhance stress tolerance. However, the effects of organic amendments vary according to the type of organic material, initial soil fertility, grape cultivar, and environmental conditions. Kokkonen et al. (2025) found that some organic treatments had only limited effects on leaf nutrient concentrations, yield, and grape juice composition, while certain treatments even reduced yield, indicating that organic fertilization practices need to be optimized according to specific vineyard conditions.

This study investigates the effects of organic fertilization on vineyard soil health, nutrient uptake, and fruit quality, with particular emphasis on the responses of the integrated "soil–grapevine–fruit" continuum. Changes in soil organic matter, nutrient availability, physical properties, biological activity, and microbial functions will be evaluated, and their potential contributions to improved nutrient uptake efficiency, yield components, and fruit quality traits, including sugar content, acidity, phenolic compounds, and other biochemical characteristics, will be further examined. This study is expected to provide a scientific basis for reducing dependence on chemical fertilizers and achieving high-yield, high-quality, and sustainable grape production.

2 Types and Characteristics of Organic Fertilizers Used in Grapevines

2.1 Animal- and plant-derived organic fertilizers

Animal- and plant-derived fertilizers in vineyards commonly include manure-based inputs and composted crop residues. Vineyard studies have tested farmyard manure, pig manure, sheep manure, composted steer manure, and mixtures of pruning residues or straw with farm manure, showing that these materials can improve soil properties and, in many cases, vine performance (Wilson et al., 2021; Hazarika et al., 2024). Plant-derived and winery-derived materials are also increasingly important, especially pruning waste, legume cover crop residues, grape pomace compost, and grape pomace vermicompost, because they recycle vineyard by-products into nutrient sources and organic matter inputs (Kokkonen et al., 2025).

These materials differ markedly in nutrient composition and decomposition characteristics. For example, Kokkonen et al. (2025) reported substantial differences in the dry-basis concentrations of nitrogen (N), phosphorus (P), and potassium (K) between compost and vermicompost derived from grape pomace, with grape pomace compost containing higher nutrient concentrations than grape pomace vermicompost. More broadly, compost nutrient composition, organic carbon content, and biological activity vary with feedstock origin and processing, so materials with similar sources can still produce different nutrient release patterns and vine responses (Mitropoulou et al., 2025). Organic amendments usually decompose more slowly than mineral fertilizers, providing nutrients over a longer part of the growing season, but this gradual release can delay vine uptake in the first years after application (Lucchetta et al., 2023).

2.2 Bio-organic fertilizers and microbial amendments

Bio-organic fertilizers combine organic nutrient sources with living microbial inoculants. In grapevine systems, these inoculants include *Azospirillum*, phosphate-solubilizing bacteria, potash-solubilizing bacteria, *Trichoderma harzianum*, *Bacillus amyloliquefaciens*, arbuscular mycorrhizal fungi, and fungal consortia added to composts or other carriers (Hazarika et al., 2024; Liu et al., 2024). Their function extends beyond direct nutrient supply because beneficial microbes can increase nutrient availability, modulate phytohormones, improve root development, and suppress pathogenic organisms (Kumar et al., 2022; Liu et al., 2024).

Studies on grapevines have shown that microbial enrichment can promote nutrient mineralization and enhance soil biological fertility. Hazarika et al. (2024) reported that the combined application of organic amendments, biofertilizers, and biodynamic preparations increased soil total and available nutrient contents, cation exchange capacity, and bacterial abundance, while also improving the micronutrient status of grapevine leaves. Bio-organic fertilizers containing *Bacillus* or *Trichoderma* increased soil organic matter, available N, P, and K, enhanced catalase, urease, sucrase, and nitrate reductase activities, and improved seedling shoot and root growth (Liu et al., 2024). Likewise, compost inoculated with fungal consortia enhanced soil enzyme activity, while long-term compost use promoted microbial biomass, phosphorus-solubilizing bacteria, and enzymes involved in nutrient turnover (Lucchetta et al., 2023; Lucchetta et al., 2025). However, microbial amendments are not always sufficient as stand-alone replacements for mineral fertilization, especially where soil organic matter is low and nitrogen supply is limiting (Lisek and Popińska, 2025).

2.3 Factors determining organic fertilizer efficiency

A central factor determining the efficiency of organic fertilizers is the carbon-to-nitrogen ratio, because it strongly regulates whether nitrogen is mineralized and released to the vine or temporarily immobilized by microorganisms. Organic amendments with a C/N ratio below 30 generally release mineral N, whereas higher ratios tend to favor immobilization and reduce immediate N availability (Baldi et al., 2022). Shen et al. (2024), in a meta-analysis of agricultural residues, further demonstrated that an initial carbon-to-nitrogen ratio (C/N) of approximately 25-30 is generally more favorable for improving compost maturity and nutrient accumulation, whereas a C/N ratio of 30-35 often prolongs the composting period. This issue is especially relevant for winery wastes, since their lignin, cellulose, and polyphenol contents can slow decomposition unless the composting process is properly balanced and matured (Mitropoulou et al., 2025).

Efficiency also depends on application rate, maturity of the amendment, and environmental conditions in the soil. In degraded vineyard soils, compost applied at 22.4-33.6 t/ha increased soil N, C, pH, exchangeable K and Ca, available P, and petiole N, P, and K, while improving pruning weight, berry weight, and later vine yield without altering juice soluble solids or acidity (Wilson et al., 2021). Deep or repeated compost application also increased organic carbon, humification, microbial biomass, and shoot growth, and organic fertilization in semiarid vineyards enhanced aggregate stability, microbial activity, and long-term C and N protection in soil (Burg et al., 2023; Fracetto et al., 2025).

Responses vary with cultivar, soil type, rainfall, and prior fertility status, and excessive or overly rapid N mineralization can stimulate vegetative growth while reducing yield or berry quality (Kokkonen et al., 2025). Organic fertilizer efficiency in vineyards emerges from the interactions among fertilizer characteristics, application management, soil properties, grape cultivar, environmental conditions, and vineyard management practices, which collectively regulate responses across the soil-grapevine-fruit continuum (Figure 1). Accordingly, an effective organic fertilization strategy should not be defined by amendment type alone, but should instead match amendment composition, maturity, application rate, and microbial activity with vine nutrient demand and site-specific soil conditions.

3 Effects of Organic Fertilization on Vineyard Soil Health

3.1 Improvement of soil physical properties

Organic fertilization can consistently improve soil aggregation, porosity, and bulk density in vineyards. In a 10-year experiment conducted in a semiarid Mediterranean vineyard, the application of pruning residues combined with sheep manure or the use of a legume cover crop increased the proportion of stable soil aggregates compared with inorganic fertilization (García-Orenes et al., 2016). In a three-year greenhouse grapevine experiment, Wu et al. (2024) reported that organic fertilizers reduced soil bulk density and increased porosity, whereas the chemical fertilization control showed the lowest soil porosity.

These improvements in soil structure are closely associated with organic matter inputs. Reviews of viticulture have shown that organic fertilization can improve soil structure and increase soil organic matter (SOM) content, while compost derived from winery wastes has also been shown to enhance physical properties such as soil water-holding capacity and aeration (Cataldo et al., 2021). In semiarid ecosystems, organic management promoted carbon and nitrogen retention within deeper soil macroaggregates and strengthened long-term soil structural integrity, indicating that these structural benefits are not restricted to the surface soil layer (Fracetto et al., 2025). Studies of orchard soils have shown similar trends: organic fertilization reduced soil bulk density, increased porosity and saturated hydraulic conductivity, and increased the proportion of macroaggregates, thereby creating a healthier soil environment for root growth (Su et al., 2026).

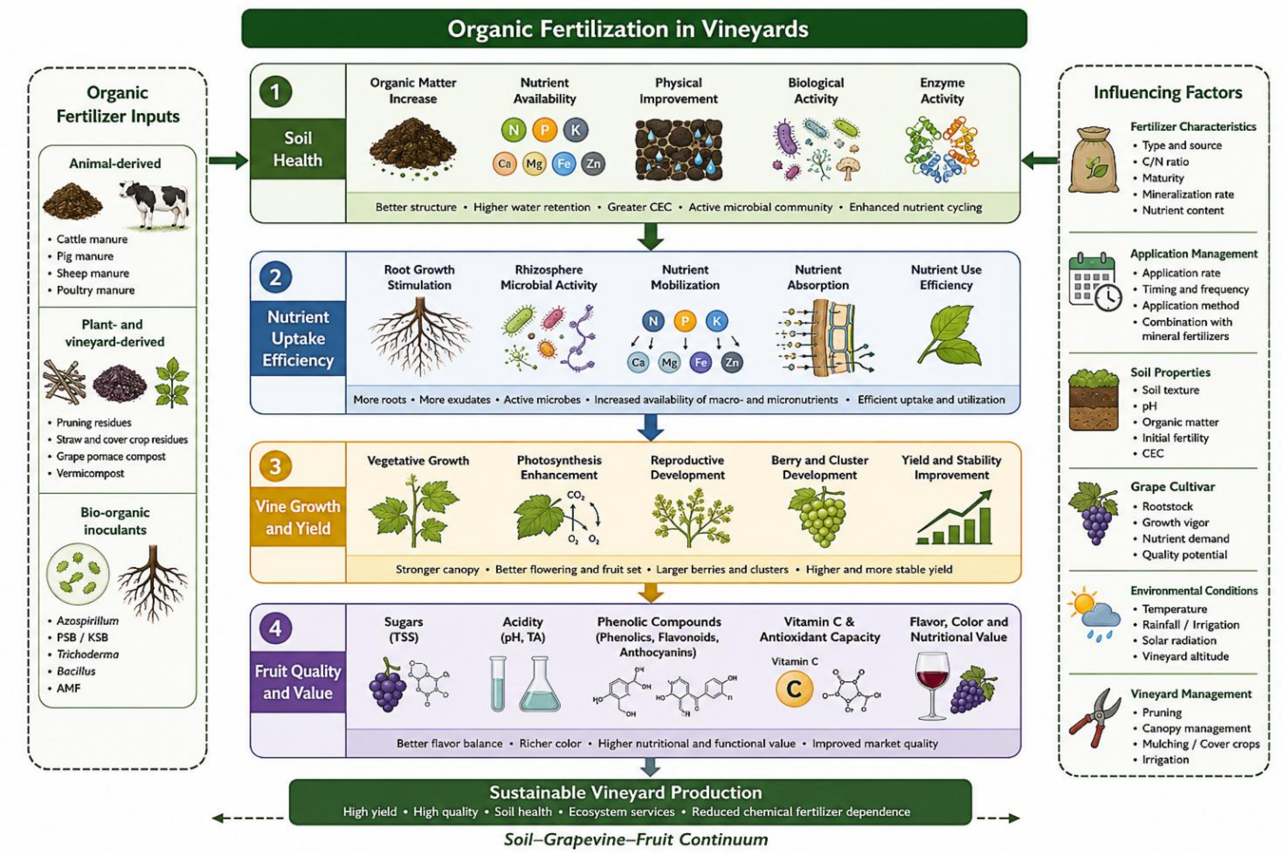

Figure 1 Conceptual framework illustrating the effects of organic fertilization across the soil–grapevine–fruit continuum

Image caption: Organic fertilization improves soil physicochemical properties, microbial activity, and nutrient cycling, thereby promoting root and rhizosphere processes and enhancing nutrient availability, uptake, and utilization efficiency. These improvements subsequently regulate grapevine vegetative growth, reproductive development, yield formation, and berry quality. The magnitude and direction of these effects are jointly influenced by fertilizer characteristics, application management, soil properties, grape cultivar, environmental conditions, and vineyard management practices. Collectively, these interconnected processes contribute to synergistic improvements in vineyard productivity, fruit quality, soil health, and the overall sustainability of grape production

3.2 Regulation of soil chemical fertility

A key chemical effect of organic fertilization in vineyards is the accumulation of soil organic matter and carbon pools. In a terraced Cabernet Sauvignon vineyard, three consecutive years of compost application increased soil organic matter (SOM) content. In Mediterranean and tropical vineyards, organic fertilization also increased total organic carbon and labile carbon and improved the balance between humic and fulvic acid fractions, thereby enhancing soil carbon stability (García-Orenes et al., 2016; Lucchetta et al., 2023; Fracetto et al., 2024). Broader agronomic studies have likewise shown that increases in SOM provide an important foundation for subsequent improvements in soil fertility, aggregate structure, and nutrient-buffering capacity (Xing et al., 2025).

Organic fertilization generally increases nutrient availability, particularly the supply of nitrogen (N), phosphorus (P), and potassium (K), although nutrient release is usually slower than that from mineral fertilizers. In vineyards, compost- and manure-based treatments can increase soil total N, available P, and water-soluble carbohydrates and, in some systems, also increase available N and K. In a disturbed hillslope vineyard, Lucchetta et al. (2023) found that compost improved mineral nutrient availability, but a significant increase in leaf N content became evident only after three consecutive years of application. This was associated with the relatively slow decomposition of organic matter and the initial microbial immobilization of newly mineralized N. Such slow-release characteristics can prolong nutrient supply and improve nutrient retention, although short-term responses may be limited and can vary among grape cultivars.

Organic fertilization generally has positive effects on soil pH, cation exchange capacity, and nutrient retention, although responses are not entirely consistent across studies. In a degraded vineyard, compost application increased soil pH and the concentrations of exchangeable K, Ca, Mn, and available P, while reducing P fixation (Wilson et al., 2021). In a grapevine study, Wu et al. (2024) showed that organic fertilizer buffered changes in soil pH and reduced soil alkalinity compared with chemical fertilizer. Broader soil-health studies further indicate that organic inputs can buffer soil acidification and enhance nutrient retention by increasing cation exchange capacity (CEC) and soil surface reactivity (Xing et al., 2025). Porous materials such as zeolite can further reduce nutrient leaching losses in vineyard soils (Doni et al., 2021).

3.3 Effects on soil biological activity

Organic fertilization increases microbial biomass and reshapes microbial community structure in vineyard soils. After a decade of organic management, vineyard soils had higher microbial biomass and altered microbial composition relative to inorganic fertilization, including increased fungal and Gram-positive bacterial abundance (García-Orenes et al., 2016). In disturbed hillslope vineyards, compost increased microbial growth from the second year onward and shifted communities toward copiotrophic and phosphorus-solubilizing bacteria while reducing pathogenic fungal strains (Lucchetta et al., 2023).

Organic fertilization also enhances enzyme activities involved in nutrient cycling. Vineyard experiments documented higher dehydrogenase, protease, urease, β-glucosidase, and phosphomonoesterase activity under organic systems than under inorganic fertilization (García-Orenes et al., 2016). Compost-treated vineyards showed stronger enzyme activity, especially for enzymes involved in the phosphorus cycle, and fungal-inoculated pruning-waste compost further increased soil enzyme activity (Lucchetta et al., 2023; Lucchetta et al., 2025). Additional grape studies found increases in catalase, dehydrogenase, urease, phosphatase, and other enzyme activities after organic fertilizer application (Tangolar et al., 2020; Wu et al., 2024). Broader long-term fertilization evidence suggests that organic inputs favor a more diverse and stable microbial community and slower, more regulated nutrient transformations than chemical fertilization alone.

4 Effects of Organic Fertilization on Nutrient Uptake in Grapevines

4.1 Regulation of macronutrient uptake

Organic fertilization often increases nitrogen availability and uptake, but the response depends strongly on amendment type and the balance between organic and mineral N sources. Bio-organic fertilizer increased soil available N and improved seedling growth in grapevine, while sewage sludge compost increased nitrate availability and vine N status, and integrated N management with 60%-80% mineral N plus 20%-40% organic and biofertilizer improved growth, yield, and berry quality better than mineral N alone (Muhammed et al., 2023). Organic amendments can also increase leaf P content and soil available P, as shown for grape pomace compost and vermicompost, poultry manure-based fertilization, and combined organic-biofertilizer treatments (Kokkonen et al., 2025). However, vineyard evidence is mixed because compost or vermicompost did not always increase leaf N, and long-term field studies in low-organic-matter soils found that organic fertilizers and AMF were not sufficient substitutes for mineral N supply.

Potassium uptake also responds positively to many organic fertilization programs, but the effect is shaped by initial soil fertility and by interactions with other nutrients. Municipal organic waste compost increased vine K status in Sangiovese, commercial organic fertilizers raised soil total and available K in greenhouse grapes, and grape pomace compost provided higher K input than pomace vermicompost on a dry-matter basis (Baldi et al., 2022; Wu et al., 2024). More generally, Hu et al. (2023) found that K supply can also stimulate P uptake and redistribute nutrients among grapevine organs, with root K status and soil available K closely associated with scion K accumulation. Seasonal nutrient-partitioning studies show that K demand peaks after bloom and during berry development, and that nutrient distribution differs among organs and production systems, so the effect of organic K sources depends on synchronization with these periods of high uptake (Chen et al., 2025; Wang et al., 2026).

4.2 Effects on secondary and micronutrient nutrition

Organic fertilization can modify calcium and magnesium uptake, but the direction and magnitude of change are less consistent than for N, P, and K. Organic nutrition significantly affected leaf Mg in high-altitude grapevines and generally enhanced mineral composition, while long-term field data showed that some biofertilizer treatments increased soil Mg and pH, and liming improved leaf Ca status in one cultivar (Lisek and Popińska, 2025). In 'Syrah', goat manure increased must Mg in one season but reduced must Ca in others, indicating that secondary nutrient responses can vary by year and tissue evaluated (da Silva et al., 2024). More broadly, organic additions are reported to supply Ca and Mg, lower pH through organic acid release, and improve root-system performance, which can favor secondary nutrient acquisition under some soil conditions (Hasan et al., 2023).

Micronutrient availability often improves under organic fertilization, especially when organic amendments are combined with beneficial microorganisms. In grapevine, integrated organic amendments with Azospirillum, phosphate-solubilizing bacteria, potash-solubilizing bacteria, and Trichoderma produced the highest leaf Mn and Zn concentrations and increased soil Mn and Zn availability (Hazarika et al., 2024). Poultry manure with organic foliar fertilization significantly affected Fe, Cu, and other micronutrients in leaves, and organic nutrition generally enhanced leaf mineral content under high-altitude conditions (Tutuş and Sensoy, 2024). A three-year field study in 'Royal' grapes also showed treatment-related variation in Fe, Zn, B, Ca, and Mg accumulation, with some organic fertilizer–tillage combinations producing higher mineral contents, although these interactions were strongly year-dependent (Kaya et al., 2025). Seasonal uptake studies further show that boron uptake peaks during flowering, while Fe and Zn can accumulate to unusually high concentrations in specific organs or stages, reinforcing that micronutrient management under organic fertilization should be timed to developmental demand (Chen et al., 2025; Wang et al., 2026).

4.3 Root and rhizosphere mechanisms of nutrient acquisition

Organic fertilization influences nutrient acquisition partly by improving root growth, architecture, and activity. In grapevine seedlings, bio-organic fertilizers promoted root expansion, increased root activity, and up-regulated genes related to cell wall loosening and auxin signaling, consistent with stronger root growth and earlier attainment of transplantable shoot size (Liu et al., 2024). Broader rhizosphere evidence indicates that root traits such as lateral root density, root hair abundance, fine-root development, and exudation capacity are central to nutrient uptake because they enlarge the absorbing surface and help recruit beneficial microorganisms (Araujo et al., 2025). Organic inputs can support these processes by improving root-zone conditions and encouraging root-hair formation and root surface area expansion (Hasan et al., 2023).

Rhizosphere microorganisms are a second major mechanism through which organic fertilization enhances nutrient mobilization. Bio-organic fertilizer increased bacterial diversity and the abundance of symbiotic N-fixing Proteobacteria and Actinobacteria in grapevine rhizosphere soil, while combined organic amendments and biofertilizers increased bacterial and Actinomycete abundance in vineyards (Liu et al., 2024). Mechanistically, PGPR and related rhizosphere microbes convert plant-unavailable N, P, and Zn into available forms, produce phytohormones and siderophores, and enhance nutrient solubilization and nitrogen fixation through root-microbial crosstalk (Feng et al., 2026). Organic phosphorus mobilization is also regulated by interactions among amendment chemistry, root traits, and microbiome functions such as proton release, organic acid exudation, and phosphatase activity.

Improved nutrient uptake under organic fertilization is mediated by both direct changes in root architecture and indirect regulation through the rhizosphere microbiome (Figure 2). These two pathways interact to increase the effective nutrient-absorbing surface and convert poorly available soil nutrients into forms more readily accessible to grapevine roots.

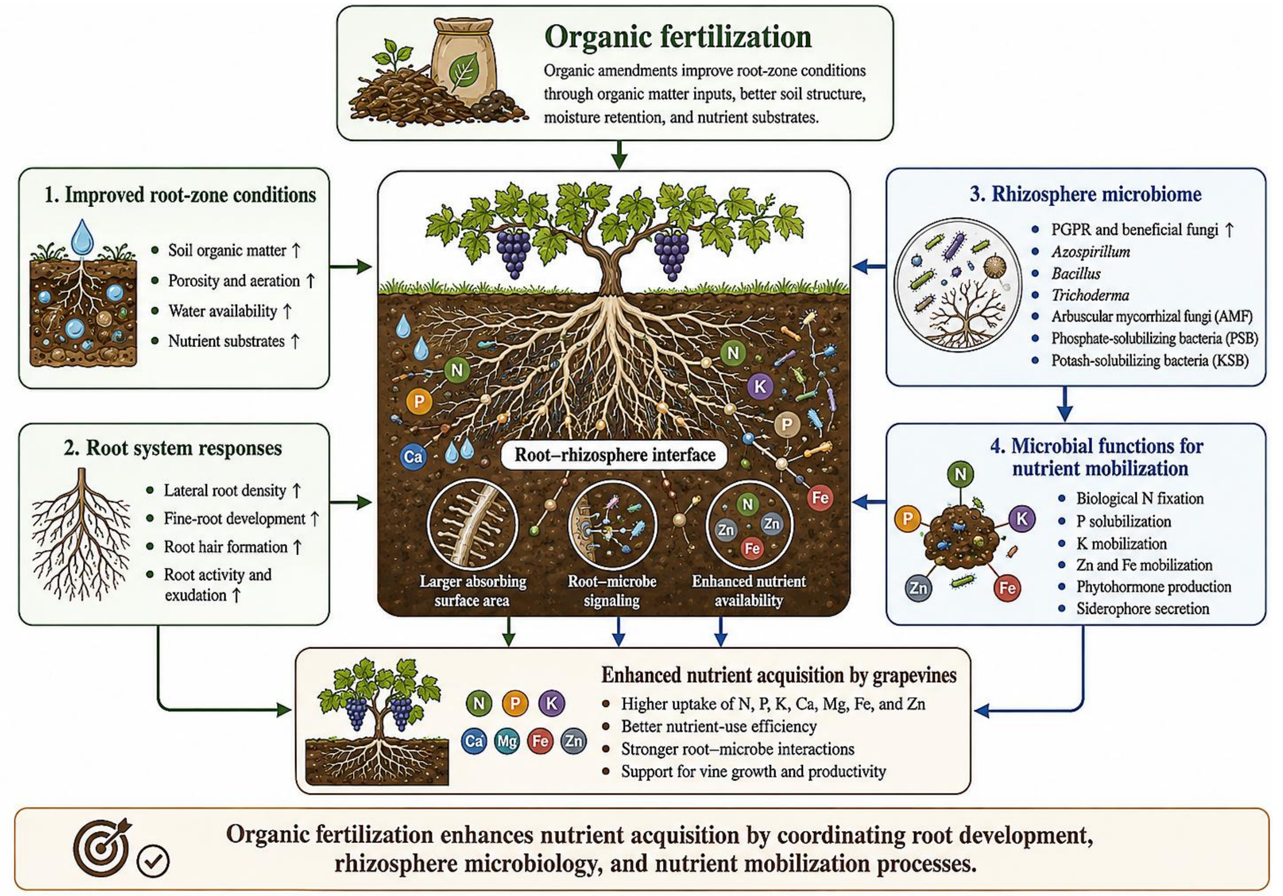

Figure 2 Root–rhizosphere mechanisms underlying nutrient acquisition under organic fertilization

5 Effects of Organic Fertilization on Grapevine Growth and Yield Formation

5.1 Effects on vegetative growth

When nutrient release is synchronized with grapevine demand, organic fertilization generally promotes shoot growth, leaf area expansion, and canopy development. Chen et al. (2023) found that, in drip-irrigated seedless white grapes, combined organic and inorganic fertilization increased new shoot length by 3.16%-11.88% and leaf midrib length by 7.35%-15.15% compared with inorganic fertilization alone. In Flame Seedless grapes, partial replacement of mineral nitrogen with compost, biofertilizer, or humic acid increased leaf area, pruning wood weight, and total chlorophyll content (Abd EL-Rahman et al., 2021). Similar improvements were also observed over three consecutive growing seasons when mineral nitrogen was partially replaced with organic and biological nitrogen sources (Alsalhy et al., 2021). Compared with the 100% mineral nitrogen treatment, Red Roomy grapevines under partial substitution treatments developed longer shoots, more leaves, and larger leaf areas. Bio-organic fertilizers also promoted grapevine seedling growth, allowing seedlings to reach the target shoot size 1-4 weeks earlier (Liu et al., 2024; El-Salhy et al., 2025). In a terraced Cabernet Sauvignon vineyard, compost application promoted vegetative growth relative to chemical fertilization, while in semiarid tropical vineyards, organic fertilization improved soil conditions and increased crop yield under adverse environmental conditions (Lucchetta et al., 2023; Fracetto et al., 2024).

Improvements in vegetative growth are usually accompanied by enhanced leaf nutrient status and photosynthetic performance. Under arid conditions, combined organic and inorganic fertilization significantly increased transpiration rate, stomatal conductance, and net photosynthetic rate in grapevines (Chen et al., 2023). Partial replacement of synthetic nitrogen with organic nitrogen improved seedling photosynthetic performance and root growth, with intermediate substitution rates producing the greatest enhancement in photosynthesis, whereas excessively high substitution rates could exert inhibitory effects (Han et al., 2025). Piva et al. (2020) reported that organic and biodynamic management also increased leaf photosynthetic activity, Rubisco efficiency, PSII quantum yield, SPAD index, and shoot growth in young BRS Carmem grapevines during at least one growing season. However, these beneficial effects have certain limitations. In a Riesling vineyard trial, organic and biodynamic management reduced lateral leaf area, leaf area index (LAI) during ripening, pruning weight, and some physiological performance indicators compared with integrated management, although canopy size remained within an acceptable range for maintaining normal assimilation capacity (Döring et al., 2015).

5.2 Effects on reproductive development

Organic fertilization affects reproductive development mainly by altering vine nutritional balance before and after bloom. Evidence from Riesling indicates that reduced physiological performance after full bloom under organic and biodynamic management can limit berry size determination and reduce cluster weight when water competition from cover crops is not controlled (Döring et al., 2015). By contrast, integrated organic-mineral programs in warmer regions generally hastened maturation and improved fruiting, suggesting that better nutrient balance and canopy function support flowering, fruit set, and early berry growth (Alsalhy et al., 2021; El-Salhy et al., 2025). Organic substitution with reduced N plus organic fertilizer also improved photosynthetic efficiency and N utilization in Shine Muscat, factors closely associated with reproductive performance (Huang et al., 2026). Seasonal uptake studies further indicate that flowering is a critical period for N and B demand, while berry bulking is a key phase for P, Ca, and Mg acquisition, so the reproductive benefit of organic fertilization depends on whether nutrient mineralization matches these stages (Saleh et al., 2026).

Effects on cluster development and berry size are better documented and generally positive under well-balanced organic fertilization. In Flame Seedless, all combined fertilization treatments increased yield and improved cluster and berry traits relative to mineral fertilization alone. In Red Roomy, combined fertilization increased cluster and berry characteristics, and the triple-form treatment increased berry number by 21.49% and yield by 12.09% while also improving berry sugars and anthocyanin (El-Salhy et al., 2025). In a two-year Shine Muscat field study, vertical berry diameter and single-berry weight had significant positive effects on total yield, indicating that organic fertilizer substitution enhanced production partly by improving berry morphology (Huang et al., 2026). Short-term biostimulant evidence points in the same direction, with amino acid treatments increasing cluster length, cluster width, cluster weight, berry number per cluster, 100-berry volume, and yield per vine, although those results reflect one-season responses rather than accumulated soil effects (Saleh et al., 2026).

5.3 Effects on yield and production stability

Yield per vine and cluster productivity usually improve under moderate organic substitution or combined fertilization. In arid drip-irrigated vineyards, combined organic-inorganic fertilization increased yield by 6.68%-19.12%, with the 50:50 organic-to-inorganic ratio recommended under 720 mm irrigation (Chen et al., 2023). In Shine Muscat, reducing N by 20%-30% and adding organic fertilizer increased yield by 18.2% and 96.0% under the 0.8N + OF treatment across two seasons and delivered the highest economic return (Huang et al., 2026). Wu et al. (2024) found that two commercial organic fertilizers increased yield by 19.04% and 16.26%, whereas sheep manure and fermented corn stalk residue decreased yield, showing that material quality strongly affects productivity. Medium-term Mediterranean field data showed similar yields under organic and inorganic fertilization after 10 years, while compost in a restored hillslope vineyard produced a trend toward higher first-year yield with improved vegetative performance and nutrient uptake (García-Orenes et al., 2016; Lucchetta et al., 2023).

Long-term yield stability under organic nutrient management appears achievable, but it depends on balanced formulations and local conditions rather than on organic inputs alone. Reviews of tropical and sustainable viticulture converge that nutrient-specific, integrated fertilization is the most reliable route to sustaining productivity and grape quality over time (Cataldo et al., 2021; James et al., 2023). Multi-year and long-term studies show that organic fertilization can stabilize soil carbon, microbial biomass, and nutrient cycling, which supports durable production capacity (Fracetto et al., 2024). However, field comparisons in Riesling found lower growth and yield under organic and biodynamic systems than under integrated management, and subtropical trials with grape pomace compost or vermicompost found negligible benefits in Chardonnay and reduced yield in Isabella (Döring et al., 2015; Kokkonen et al., 2025).

6 Effects of Organic Fertilization on Grape Fruit Quality

6.1 Regulation of sugar and organic acid accumulation

Organic fertilization often increases soluble solids and soluble sugars when nutrient supply is balanced rather than excessive. In Isabel Precoce grapes, organic fertilization with up to 90 kg/ha N increased soluble solids to about 17 °Brix, total soluble sugars, reducing sugars, and the soluble solids-to-acidity ratio (De Lima et al., 2021). In Superior grapevines, replacing part of mineral N with chicken manure and biofertilizer increased total soluble solids, reducing sugars, and berry quality progressively as mineral N was reduced from 100% to 40% (Muhammed et al., 2023). In Shine Muscat, reducing N by 20%-30% while adding organic fertilizer consistently increased total sugar and the sugar–acid ratio, and potassium availability emerged as the key factor regulating sugar accumulation and flavor coordination (Huang et al., 2026). Multi-year Royal grape studies likewise showed that tillage plus organic amendments significantly altered berry sugar composition, with treatment-dependent increases in sucrose, glucose, and fructose and the highest rhamnose, galactose, and xylose under broccoli fertilizer in some combinations (Kaya et al., 2024b).

Effects on titratable acidity and sugar–acid balance are generally favorable but less uniform than effects on sugar accumulation. Partial replacement of mineral N with organic and biofertilizers decreased total acidity in Superior berries while increasing the TSS/acid ratio (Muhammed et al., 2023). In Shine Muscat, Huang et al. (2026) found that the 0.8N + organic fertilizer treatment increased the sugar–acid ratio together with total sugar and vitamin C. Increased organic fertilization with reduced chemical fertilizer also lowered grape juice pH in arid vineyards, consistent with improved flavor balance (Wu et al., 2021). However, acidity responses are not consistent across cultivars: pH and titratable acidity were unaffected in white seedless grapes under organic, conventional, and integrated fertilization, and organic fertilization did not affect most quality traits of ‘Syrah’ must (Koureh et al., 2019; da Silva et al., 2024). This variability is biologically plausible because sugar and acid profiles are strongly stage-dependent, with sugars rising and organic acids shifting markedly from veraison to ripening (Yılmaz et al., 2024).

6.2 Effects on phenolic and aroma-related compounds

Organic fertilization often enhances anthocyanins, flavonoids, and total phenolics, especially when nutrient supply promotes moderate stress and balanced ripening. In white seedless grape, organic fertilization produced the highest total phenolics, catechin, and quercetin-3-galactoside, while antioxidant activity and total flavonoids were highest under organic or integrated systems (Koureh et al., 2019). In Royal grapes, three-year studies showed significant treatment effects on phenolics and anthocyanins, with broccoli-based fertilization generally producing the strongest increases and specific tillage-fertilizer combinations enhancing compounds such as resveratrol, pterostilbene, vanillic acid, and trans-caffeic acid (Kaya et al., 2024b). Organic and combined fertilization schedules in Cabernet Sauvignon also increased berry quality through higher total phenols or tannins and linked these changes to shifts in soil bacterial communities associated with anthocyanin and tannin accumulation (Wang et al., 2021). Soil-conditioner work supports the same direction, showing higher anthocyanins, tannins, and total phenols than standard NPK or organic fertilizer alone (Jiang et al., 2024). Phenolic responses are not universally positive: in Isabel Precoce, the highest polyphenol and anthocyanin contents occurred with mineral N up to 60 kg/ ha without organic fertilization (De Lima et al., 2021).

Evidence on volatile compounds and aroma characteristics is more limited, but fertilizer regime clearly affects berry aroma composition. General berry-development studies by Yılmaz et al. (2024) show that aroma synthesis becomes prominent during ripening, after sugar accumulation and pigmentation intensify. In Hanxiangmi table grape, nutrient-related K treatments increased volatile free aroma compounds, especially terpenes such as linalool, nerol, and citronellol, alongside higher TSS and lower acidity under the combined treatment (Chen et al., 2022). More broadly, vineyard management studies conclude that fertilization can substantially alter sugar content, polyphenolic profiles, and therefore sensory attributes of grapes and wines (Jiang et al., 2024).

6.3 Effects on external and nutritional quality

Organic fertilization can improve berry size, firmness, color, and overall appearance, but these traits respond strongly to fertilizer formulation. In Shine Muscat, organic fertilizer substitution improved berry morphology, and path analysis identified vertical diameter and single-berry weight as major contributors to yield gains (Huang et al., 2026). In greenhouse grapes, commercial organic fertilizers increased early yield, whereas sheep manure and corn-stover treatments reduced it, implying that amendment maturity and nutrient balance affect berry development and marketable appearance (Wu et al., 2024). Increased organic fertilizer with reduced chemical fertilizer also improved flesh firmness in arid-area grapes (Wu et al., 2021). Evidence from related preharvest organic stimulants is consistent with these traits being nutritionally sensitive: molasses-based treatments improved berry coloration, firmness, and TSS while lowering acidity in Crimson Seedless (Samaan et al., 2026). Berry color is especially important in red cultivars because it directly affects consumer appeal and price, and improvements in anthocyanin accumulation generally translate into better external appearance (Salama et al., 2023).

The strongest consensus concerns nutritional quality and antioxidant capacity. Koureh et al. (2019) reported that organic fertilization produced the highest antioxidant activity, total phenolics, and valuable flavonoids in white seedless grapes. In Shine Muscat, organic substitution increased vitamin C content (Huang et al., 2026). Royal grape studies of Kaya et al. (2025) further showed that organic fertilization altered berry mineral composition, hormone levels, and antioxidant enzyme activities, indicating that nutritional improvement extends beyond sugars and phenolics alone.

7 Integrated Organic Nutrient Management in Vineyard Production

7.1 Combined use of organic and mineral fertilizers

Partial substitution of chemical fertilizers with organic fertilizers is the most consistently supported strategy. In Shine Muscat, reducing N by 20%-30% and adding organic fertilizer increased yield, improved sugar–acid balance, and produced the highest economic return, whereas substitution above 40% reduced economic benefit (Huang et al., 2026). In Superior grapevines, mineral N at 60% with 20% organic and 20% biofertilizer improved growth, yield, and berry quality, and replacing 40% of mineral fertilizer was recommended as a practical reduction target (Muhammed et al., 2023). Similar results were reported by Alsalhy et al. (2021) in Flame Seedless, where using 25%-50% of N requirement as mineral fertilizer plus organic and biofertilizer improved vine nutrient status, yield, fruit quality, and packable yield while lowering production costs and pollution risk. Humic- and fulvic-acid substitution also fit this pattern, with 75% of N requirement plus humic or fulvic acid improving vine nutrient status, yield, fruit quality, and some soil properties while reducing environmental costs from excess mineral N (El-Salhy et al., 2023).

The agronomic rationale is that mineral fertilizers provide immediate nutrient availability, whereas organic fertilizers strengthen long-term soil fertility. Combined organic–inorganic fertilization increased soil available N, P, and K, shoot growth, photosynthesis, yield, and fruit quality under drip irrigation in an arid vineyard, with 50% organic plus 50% inorganic fertilizer recommended at 720 mm irrigation (Chen et al., 2023). Commercial organic fertilizers combined with inorganic basal fertilization also improved early Shine Muscat yield and provided more comprehensive nutrient supply than chemical fertilizer alone (Wu et al., 2024). More generally, Luo et al. (2024) reported that joint organic–mineral fertilization improves soil P activation better than mineral fertilizer alone, which helps explain its value in low-fertility soils. However, balance is essential: sewage-sludge compost increased N availability and vegetative growth in Sangiovese, but excessive mineralization reduced yield and berry quality, while overuse of compost plus mineral fertilizer raised exchangeable nutrients without improving vine response in subtropical vineyards (Baldi et al., 2022; Kokkonen et al., 2025).

7.2 Coordination of organic fertilization with vineyard management

Organic fertilization is more effective when coordinated with irrigation and soil-moisture management. In extremely arid vineyards, imbalanced water–fertilizer systems limited yield and quality, whereas combined organic–inorganic fertilization under optimized drip irrigation improved soil nutrients, vine growth, yield, and berry quality (Chen et al., 2023). In semi-arid nutrient-poor vineyards, spent mushroom compost mulch increased soil water content, leaf N, vegetative growth, and yield, while straw mulch improved soil water content, reduced soil temperature, and improved plant water status and gas exchange (Mairata et al., 2024). Broader dryland evidence supports this mechanism: organic mulching reduces evaporation, conserves water in the root zone, limits erosion, and increases soil organic matter and water-holding capacity (Demo and Bogale, 2024).

Integration with cover cropping, mulching, and soil conservation is also central to vineyard nutrient management. Cover crops can increase organic matter, reduce erosion, improve biodiversity, and supply nutrients, but permanent cover crops can also compete with vines for water and nutrients. Mairata et al. (2024) pointed out that organic mulches provide a useful alternative because they control weeds and erosion while reducing compaction and increasing porosity, aggregate stability, and nutritional content in the shallow soil layer. Conservation tillage and plant-waste incorporation are likewise associated with better long-term soil health and yield resilience, whereas continuous cultivation can reduce organic matter and soil permeability over time (Kaya et al., 2024a). These combined practices align with broader soil-conservation principles in sustainable agriculture, where cover cropping, conservation tillage, and organic amendments preserve fertility, water, and biodiversity (Hasan et al., 2023).

7.3 Optimization of organic fertilization strategies

Optimization depends first on matching fertilizer type and application rate to vineyard requirements. The chemical composition, maturity, and mineralization rate of organic materials determine whether they support balanced vegetative and reproductive growth or push vines toward excess vigor (Baldi et al., 2022; Hasan et al., 2023). Material choice matters strongly: in nutrient-poor soils, spent mushroom compost performed better than straw or pruning-debris mulch for short-term vine development because of its richer nutrient composition and lower C/N ratio (Mairata et al., 2024). Rate also matters: grapevine seedlings responded best to 25% organic substitution with spent mushroom substrate, while higher substitution rates failed to further improve soil N, photosynthesis, or root architecture (Han et al., 2025). Reviews of vineyard fertilization similarly conclude that fertilizer systems should combine manure, mineral fertilizer, and supplemental nutrition over time, and that high mineral doses can reduce yield (Monastyrskiy et al., 2022).

Optimization also requires site- and cultivar-specific nutrient management. Vineyard fertilizer programs should be nutrient-specific and based on soil testing, plant analysis, pruning returns, and management factors that shape nutrient-use efficiency. Long-term field data collected by Lisek and Popińska (2025) in Poland showed that organic fertilizers, AMF, and biostimulants were not adequate substitutes for mineral fertilization in low-organic-matter soils, especially for N supply, and that mineral fertilization should be continuously readjusted rather than applied routinely. Subtropical vineyards also showed cultivar-dependent responses: grape pomace compost and vermicompost increased soil P and K availability, but leaf nutrient status, yield, and quality changed little in Chardonnay and sometimes declined in Isabella, especially under already adequate soil fertility or high-rainfall conditions (Kokkonen et al., 2025).

These findings support a shift from fixed fertilizer recipes toward adaptive nutrient management (Figure 3). Organic fertilizer type and substitution rate should be determined according to soil nutrient status, amendment mineralization characteristics, cultivar demand, irrigation conditions, and plant nutritional diagnosis, followed by continuous monitoring and adjustment during vineyard production.

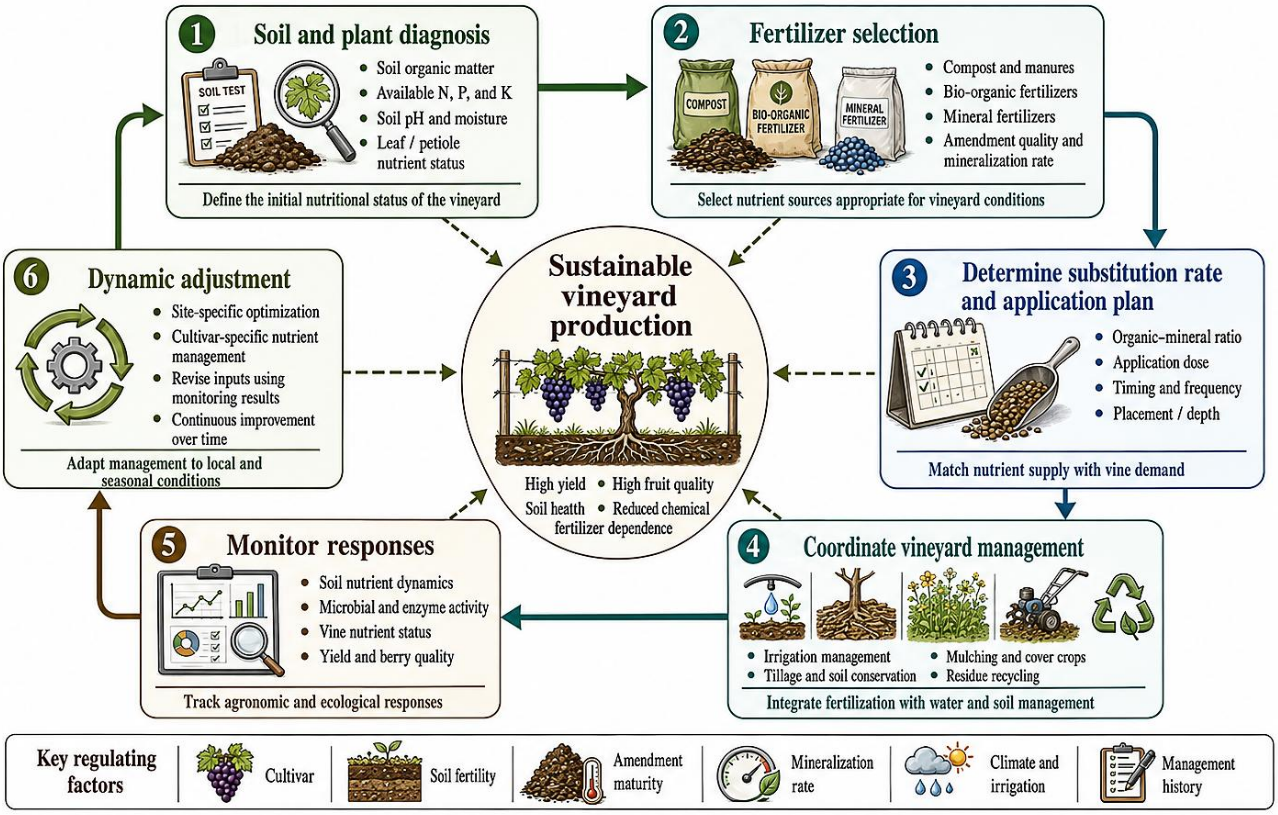

Figure 3 Integrated organic nutrient management framework for sustainable vineyard production

8 Conclusions and Future Research Directions

Existing studies indicate that the role of organic fertilizers in vineyards extends beyond simple nutrient supplementation and contributes to the overall improvement of soil health. Plant residues and other organic amendments can increase soil organic matter and nutrient levels, enhance microbial and enzymatic activities, improve soil water and aeration conditions, and strengthen agroecosystem resilience. Combined application of organic and mineral fertilizers can also promote grape yield formation while maintaining favorable soil properties, with available nitrogen, available potassium, and soil enzyme activities showing relatively close associations with yield responses.

Organic fertilization is beneficial for grape yield and fruit quality, although responses vary among cultivars and growing conditions. In ‘Shine Muscat’ grape, reducing nitrogen application by 20%-30% while supplementing with organic fertilizer increased yield, sugar-acid ratio, vitamin C content, and economic returns, with the 0.8N + OF treatment showing particularly favorable performance. Some studies have also reported that organic cultivation can enhance antioxidant activity and increase flavonoid and phenolic contents in seedless grapes. However, other studies have found higher yields under conventional fertilization or no significant effects of organic fertilizers on most quality traits of Syrah grapes, indicating that the effectiveness of organic fertilization is strongly dependent on cultivar and environmental conditions.

Current research is also constrained by factors such as soil conditions, climate, cultivar, and management practices. Soil temperature, moisture, initial fertility, texture, and pH can all influence organic fertilizer mineralization, nutrient uptake, and the resulting agronomic effects. Fertilization strategies should therefore be dynamically adjusted according to soil testing, plant nutritional status, and actual management conditions. Long-term field experiments in vineyards remain limited, and many studies have lasted only 2-3 years, which is insufficient to fully evaluate the long-term ecological and production effects of organic fertilization.

Future research should place greater emphasis on the mechanisms underlying soil-microbe-root interactions and integrate approaches such as metagenomics and metabolomics to clarify how organic fertilizers regulate nutrient cycling and the rhizosphere microenvironment. At the same time, precision organic nutrient management systems should be developed by jointly considering organic fertilizer quality, mineralization rate, irrigation, ground-cover management, cultivar-specific nutrient requirements, and local climatic conditions. Integrating soil and plant diagnostics with real-time monitoring and data-driven decision-making tools will further support dynamic fertilization and the sustainable management of vineyards.

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The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of Potassium Fertilization on Fruit Size, Sugar Accumulation, and Quality of Citrus

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Abstract With increasing consumer demand for high-quality citrus fruits, improving fruit size, sugar accumulation, and flavor attributes through nutritional regulation has become an important objective in orchard management. This study reviews the application of potassium fertilization in citrus production and summarizes recent advances in potassium uptake and transport, fruit growth, carbon metabolism regulation, and quality formation. The results indicate that appropriate potassium application can optimize nutrient allocation within citrus trees, promote the transport of photosynthetic assimilates to fruits, enhance fruit enlargement and sugar accumulation, and improve total soluble solids content and sugar–acid balance. However, citrus responses to potassium fertilization vary among cultivars, growing environments, and cultivation practices, while application timing, fertilization methods, and nutrient balance strongly influence management outcomes. Future integration of nutrient diagnosis, precision fertilization, and smart agriculture technologies may further improve potassium use efficiency and promote high-quality and sustainable citrus production.

Keywords Citrus; Potassium management; Fruit quality; Sugar accumulation; Precision fertilization

1 Introduction

Citrus is one of the most economically important fruit crops worldwide, with major production and trade systems concentrated in countries such as China, Brazil, and the United States (Abouzari and Nezhad, 2016; Spreen et al., 2020; Wen et al., 2021). With increasing consumer demand for high-quality fresh fruit, improving and stabilizing citrus yield and fruit quality has become a major objective in modern orchard production. Fruit size, total soluble solids (TSS), sugar–acid ratio, and flavor-related traits directly influence consumer acceptance and market value (Wu et al., 2021; Morales Alfaro et al., 2023). However, citrus production still faces common challenges, including inconsistent fruit size, insufficient sugar accumulation, and a low proportion of premium-quality fruits. Therefore, optimizing nutrient management has become an important approach for improving citrus fruit quality.

Potassium (K) is one of the essential macronutrients required for plant growth and development and plays critical roles in carbon metabolism, photosynthesis, osmotic regulation, and assimilate transport (Hasanuzzaman et al., 2018; Johnson et al., 2022). Unlike nitrogen and phosphorus, which are mainly involved in structural components, potassium primarily regulates plant growth and yield formation through enzyme activation, stomatal movement, and source-sink relationships (Sardans and Peñuelas, 2021). In leaves, adequate potassium supply promotes photosynthetic carbon assimilation and enhances the transport of photosynthetic products to sink organs such as fruits. In contrast, potassium deficiency reduces photosynthetic capacity, restricts carbohydrate accumulation, and ultimately inhibits plant growth and yield formation (Tränkner et al., 2018; Shah et al., 2024). However, excessive potassium application may also reduce nutrient use efficiency and disturb the balance among mineral elements. Therefore, maintaining an appropriate potassium supply level is essential for improving crop production efficiency (Hasanuzzaman et al., 2018).

Citrus has a relatively high potassium demand, and large amounts of potassium accumulate during fruit development. Since potassium in citrus orchard soils is vulnerable to leaching losses, insufficient potassium supply often results in reduced fruit size, lower yield, and impaired fruit quality. Previous studies have demonstrated that appropriate potassium fertilization can promote fruit enlargement and enhance sugar accumulation. For example, Wu et al. (2024) reported that maintaining fruit potassium concentration at an appropriate level of approximately 1.5% in Newhall navel orange increased fruit growth rate, enhanced source–sink activity, and promoted sucrose transport from leaves to fruits, thereby improving fruit quality. In Cara Cara navel orange, potassium application at 0.50 kg per plant promoted the accumulation of sucrose, fructose, and glucose, which was closely associated with the regulation of sucrose metabolism-related enzyme activities (Wu et al., 2021). Foliar application of K_2SO_4 has also been shown to increase fruit weight, total soluble solids, soluble sugar content, and the TSS:TA ratio while reducing titratable acidity (Thu et al., 2024). Furthermore, Xu et al. (2024) found that optimized nutrient management in citrus orchards increased yield by 11.9%, single fruit weight by 2.8%, TSS by 5.9%, and total sugar content by 8.6%, indicating that balanced nutrient regulation plays an important role in improving fruit quality.

Although the importance of potassium in citrus quality formation has been widely recognized, the optimal potassium application rate, fertilizer type, and application timing remain variable under different production conditions. Citrus responses to potassium are influenced by multiple factors, including cultivar, rootstock, climatic conditions, and soil nutrient status. Moreover, excessive potassium input may lead to nutrient competition and inefficient resource utilization (Kuzin and Solovchenko, 2021; Sardans and Peñuelas, 2021). Therefore, clarifying the regulatory effects of potassium management on citrus fruit development and quality formation is important for improving fertilizer use efficiency and achieving high-quality and sustainable citrus production.

This study focuses on the effects of potassium fertilization on citrus fruit size, sugar accumulation, and quality formation, with particular emphasis on the roles of potassium in promoting fruit enlargement, regulating carbon assimilate transport, and improving sugar–acid balance. The aim is to clarify the relationship between potassium nutrition and citrus fruit quality development, thereby providing theoretical references for precision potassium management and the production of high-quality citrus fruits in modern orchards.

2 Physiological Functions of Potassium in Citrus Growth

2.1 Potassium uptake, transport, and distribution in citrus plants

Potassium in citrus is mainly absorbed by the root system and subsequently transported over long distances through the xylem and phloem to meet the physiological demands of metabolically active tissues (Wen et al., 2021; Wegner et al., 2025). Previous botanical studies have shown that after potassium is taken up from the soil, it is transported through the xylem to aboveground tissues along with the transpiration stream. Source tissues can then reload potassium into the phloem, allowing its redistribution to sink organs and partial recycling back to the root system (Dreyer et al., 2017). This recycling process has important physiological significance because potassium concentration gradients facilitate vascular transport processes, including sucrose reloading, while helping coordinate the balance between aboveground demand and root supply (Dreyer et al., 2017; Raddatz et al., 2020). Citrus plants also possess a relatively well-developed potassium transport system. Öz (2024) reported that 25 *CsHAK* genes have been identified in sweet orange (*Citrus sinensis*), and these HAK/KUP/KT transporter proteins are involved in potassium transport across the plasma membrane and within organelles.

Potassium is generally preferentially accumulated in organs with high metabolic activity, particularly leaves, where strong osmotic regulation and transport control are required. However, during citrus fruit development, fruits also function as important potassium sink organs (Sardans and Peñuelas, 2021; Jiao et al., 2022). In citrus orchards, the amount of potassium absorbed and exported by fruits is higher than that of other mineral nutrients, which explains why potassium deficiency can rapidly affect fruit quality and final yield in the current growing season.

Fertilization studies have further demonstrated that potassium supply can modify nutrient allocation patterns between vegetative organs and fruits. For example, Wen et al. (2021) showed that combined application of potassium fertilizer and organic fertilizer increased dry matter accumulation in spring flush leaves and shoots, while enhancing mineral nutrient uptake by both vegetative tissues and fruits. Root-zone potassium application also increased potassium, calcium, and nitrogen concentrations in citrus peel and pulp, indicating that external potassium supply can regulate internal nutrient distribution and promote greater nutrient transport toward developing fruit tissues (Figure 1) (Jiao et al., 2022).

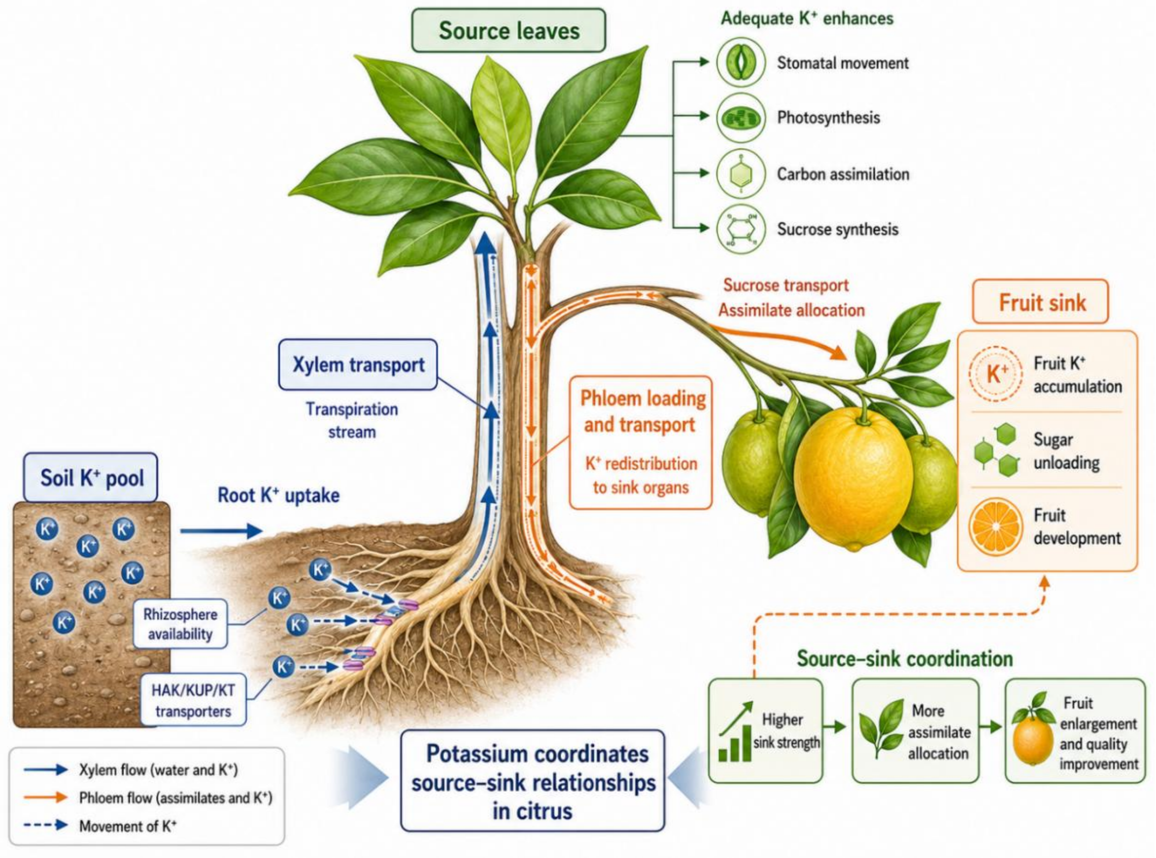

Figure 1 Potassium uptake, transport, and source–sink regulation in citrus plants

Image caption: The figure illustrates potassium uptake, transport, and source–sink regulation in citrus plants. Soil-derived K^+ is absorbed by roots through HAK/KUP/KT transporters and transported upward via the xylem. In source leaves, potassium enhances stomatal regulation, photosynthesis, carbon assimilation, and sucrose synthesis. Subsequently, K^+ facilitates phloem loading and assimilate transport toward fruit sink tissues, promoting potassium accumulation, sugar unloading, fruit enlargement, and quality improvement

2.2 Potassium regulation of photosynthesis and carbon metabolism

Potassium directly regulates stomatal function and plant water relations, and sufficient potassium supply generally improves CO_2 assimilation capacity and photosynthetic efficiency in citrus and other plant species (Wen et al., 2021; Johnson et al., 2022). Studies have shown that potassium fertilization increases the net photosynthetic rate, stomatal conductance, and intercellular CO_2 concentration in citrus cultivars prone to fruit cracking, indicating that an adequate potassium level can improve leaf gas exchange processes (Jiao et al., 2022).

Broader studies across plant species have also demonstrated that potassium deficiency reduces photosynthetic carbon assimilation capacity, leading to impaired photosynthesis and decreased assimilate utilization efficiency (Anil Kumar et al., 2024). Physiologically, these effects are closely associated with the involvement of potassium in regulating membrane potential, intracellular pH stability, osmotic balance, and enzyme systems related to photosynthesis and respiration (Raddatz et al., 2020; Jiao et al., 2022).

Potassium promotes carbohydrate synthesis in source leaves and enhances the transport of photosynthetic products to fruits, thereby facilitating carbon metabolism in citrus plants (Wen et al., 2021). In Newhall navel orange, potassium application enhanced leaf photosynthesis, increased the activity of sucrose phosphate synthase (SPS) and the expression of the *CsSPS* gene, while also improving the activities of SPS and sucrose synthase (SS) in fruits, indicating that potassium simultaneously promotes metabolic processes in both source and sink tissues (Wu et al., 2024).

Further studies by Wu et al. (2024) demonstrated that potassium supply increased the accumulation of ^{13}C-sucrose and ^{13}C-glucose in fruits, suggesting that potassium enhances carbon transport from leaves to fruits during fruit enlargement and coloration stages. This transport effect has a clear physiological basis, as potassium is one of the major osmotic regulators in phloem sap and contributes to maintaining phloem pressure flow, thereby facilitating the transport of sucrose and other solutes (Tränkner et al., 2018).

2.3 Potassium and fruit development processes

Potassium promotes citrus fruit enlargement, partly because it regulates cellular osmotic potential and turgor pressure, both of which are fundamental processes underlying cell expansion (Wen et al., 2021; Wu et al., 2024). Jiao et al. (2022) demonstrated that potassium is associated with fruit cell division, root proliferation, and enhancement of peel tissues, suggesting that potassium not only affects fruit cell expansion but also contributes to maintaining the vegetative growth system that supports fruit development. At the whole-fruit developmental level, an adequate potassium supply can increase fruit growth rate in Newhall orange, while repeated foliar applications of K_2SO_4 during citrus development can also increase individual fruit weight (Wu et al., 2024). Related orchard studies further indicate that potassium promotes fruit enlargement, improves peel coloration, and alters peel thickness; however, these effects are influenced by potassium application rate, fertilizer type, and cultivation management practices (Wen et al., 2021).

Thu et al. (2024) reported that potassium enhances citrus fruit sink strength by coordinating sugar metabolism, transporter activity, and vascular transport of assimilates. In Newhall navel orange, maintaining fruit potassium concentration at an optimal level of approximately 1.5% improved fruit quality and promoted sugar accumulation (Wu et al., 2024). During citrus fruit development, foliar application of K_2SO_4 also increased soluble sugar content, total soluble solids (TSS), and the TSS:TA ratio, while upregulating the expression of genes associated with sugar metabolism and transport, including *CsCWINV-2/6*, *CsSUT-1/2*, and *CsVPP-1/2*. These findings further support the model that potassium promotes fruit quality formation by enhancing sink strength (Thu et al., 2024).

3 Effects of Potassium Fertilization on Citrus Fruit Size

3.1 Potassium effects on fruit growth and expansion

Previous studies have shown that potassium promotes fruit growth by enhancing cell division and cell elongation, while maintaining the turgor pressure required for cell expansion during fruit development (Toor et al., 2021; Jiao et al., 2022). In citrus, potassium promotes root proliferation and improves nutrient uptake capacity, thereby indirectly supporting rapid fruit growth during the cell division and enlargement stages (Jiao et al., 2022).

The timing of potassium supply is also critical, as citrus fruits exhibit different sensitivities to potassium availability throughout their developmental stages. Thu et al. (2024) found in Nanfeng mandarin that continuous foliar application of K_2SO_4 during the cell division, cell enlargement, and maturation stages produced greater growth-promoting effects than potassium application restricted to a single developmental stage. Studies on pomelo have also identified distinct periods of high potassium demand. Approximately two months after fruit set represents a critical developmental stage, indicating that potassium supply needs to coincide with peak fruit nutrient requirements to achieve optimal effects (Magbalot-Fernandez and Guzman, 2019).

Potassium fertilization generally increases fruit weight directly. In Kinnow mandarin, soil potassium application significantly increased individual fruit weight, fruit number, and overall yield (Singh et al., 2023). In Baladi lemon cultivated under potassium-deficient soil conditions, foliar potassium application improved fruit size-related traits. Among different treatments, potassium tartrate resulted in the highest individual fruit weight and volume in 2022, while high-concentration potassium citrate increased fruit weight, volume, and dry matter content across multiple seasons (Awad et al., 2024).

Magbalot-Fernandez and Guzman (2019) reported that increasing potassium application to 225 g per tree in ‘Magallanes’ pomelo increased individual fruit weight by 22%-26%, although fruit diameter and length did not show significant changes. This indicates that potassium can enhance fruit biomass accumulation but may not necessarily alter linear fruit size parameters. Studies on Newhall orange further confirmed the role of potassium in promoting fruit growth, showing that an adequate potassium level increased fruit growth rate and overall quality, with the optimal response occurring when fruit potassium concentration was maintained at approximately 1.5% (Wu et al., 2024).

3.2 Potassium regulation of source-sink relationships

One of the important pathways through which potassium promotes fruit enlargement is by improving leaf photosynthetic capacity and enhancing the supply capacity of source tissues. Studies have shown that potassium regulates stomatal movement, plant water relations, and photosynthetic processes (Hasanuzzaman et al., 2018; Johnson et al., 2022). For example, potassium deficiency in hydroponically grown lemon plants resulted in reductions in photosynthetic rate, stomatal conductance, transpiration rate, intercellular CO_2 concentration, and pigment content, although different rootstock materials exhibited certain variations in their responses (Papadakis et al., 2023). In contrast, potassium application in citrus cultivars susceptible to fruit cracking increased photosynthetic rate, stomatal conductance, and intercellular CO_2 concentration, indicating that adequate potassium supply improves leaf gas exchange capacity (Jiao et al., 2022). Foliar potassium application in lemon also increased SPAD values, photosynthetic performance index, and leaf nutritional status, which is consistent with the enhanced activity of source tissues under sufficient potassium availability (Awad et al., 2024).

Potassium can also promote fruit enlargement by enhancing carbohydrate transport from leaves to fruits. Wu et al. (2024) found in Newhall navel orange that potassium supply simultaneously enhanced both source strength and sink strength, increased fruit growth rate, and promoted sucrose transport from source leaves to fruits. Mechanistically, potassium enhances carbon transport through the symplastic loading pathway by increasing the number of plasmodesmata and the intensity of carboxyfluorescein signal transmission, indicating improved phloem loading capacity during fruit development.

Similar patterns have been observed in Cara Cara navel orange, where potassium increased sucrose, fructose, and glucose contents by regulating the activities of sucrose metabolism-related enzymes, thereby enhancing fruit sink strength (Wu et al., 2021). Studies on other non-citrus fruit trees have also demonstrated that potassium increases carbon import rates into sink organs and promotes the activity of enzymes involved in sugar conversion, which is consistent with the “source-sink regulation” model observed in citrus (Luo et al., 2021).

3.3 Factors influencing potassium responses in citrus

Citrus genotypes do not respond uniformly to potassium fertilization. A meta-analysis by Xu et al. (2024) demonstrated that different citrus groups, including mandarins, pomelos, and sweet oranges, showed distinct growth and yield responses after optimized fertilization. Specific experiments have further confirmed these differences. For example, potassium application in pomelo substantially increased fruit set, fruit number, and individual fruit weight, but had limited effects on fruit diameter and length (Magbalot-Fernandez and Guzman, 2019). In contrast, lemon plants showed strong selectivity toward potassium sources, with different potassium fertilizers (potassium citrate, potassium tartrate, and potassium nitrate) exhibiting advantages for different fruit quality parameters (Awad et al., 2024). Rootstock type also affects potassium utilization efficiency. Papadakis et al. (2023) reported that in lemon, the effects of potassium on plant growth, photosynthetic performance, and mineral nutrient distribution were regulated by rootstock genotype.

Environmental conditions also determine the effectiveness of potassium fertilization. Due to differences in soil properties and climatic conditions, citrus responses to potassium supply are not always consistent among orchard studies (Wen et al., 2021; Papadakis et al., 2023). Among environmental factors, water management is particularly important. In sweet orange production, fertigation with only 50% of the recommended nitrogen and potassium rates achieved the highest yield and increased nutrient use efficiency by 22%; however, applying 100%

of the recommended fertilization rate did not provide additional benefits and may instead increase the risks of soil acidification and ammonium toxicity (Quaggio et al., 2019). Excessive potassium application may also cause nutrient imbalance. For example, in hydroponically grown lemon, high potassium concentrations reduced the overall uptake of phosphorus, calcium, magnesium, boron, manganese, and zinc, with these effects being particularly evident under the 6 mM potassium treatment (Papadakis et al., 2023).

Therefore, the positive effects of potassium fertilization on citrus fruit enlargement can only be achieved consistently when fertilizer rate, potassium source, application timing, cultivar characteristics, rootstock traits, and water availability are properly coordinated. Rational potassium management should be based on local production conditions and tree nutrient requirements, rather than simply increasing potassium input.

4 Effects of Potassium Fertilization on Sugar Accumulation

4.1 Potassium regulation of carbohydrate metabolism

Potassium regulates sucrose degradation during the early stage of citrus fruit development and sucrose resynthesis during the later stage, thereby affecting sugar accumulation in fruits. Wu et al. (2021) reported that potassium application in Cara Cara navel orange increased the cleavage activities of invertase and sucrose synthase (SS) during the early fruit development stage, promoting sucrose degradation into fructose and glucose. During the later ripening stage, potassium enhanced the synthesis direction activity of sucrose synthase and increased the activity of sucrose phosphate synthase (SPS), indicating that potassium promotes sucrose resynthesis during fruit maturation. This stage-dependent regulatory pattern is consistent with the general characteristics of citrus sugar metabolism, in which sucrose is the major storage sugar in citrus fruits. As a rate-limiting enzyme in sucrose biosynthesis, SPS generally shows increasing expression levels during fruit maturation and is positively correlated with sucrose accumulation (Lu et al., 2024). Studies on other fruit crops also provide supporting evidence, showing that potassium generally enhances SPS and SS activities, thereby promoting the accumulation of sucrose, glucose, and fructose and shifting carbon metabolism toward higher sugar accumulation (Zhang et al., 2018; Wang et al., 2024).

Potassium also promotes sugar accumulation by enhancing phloem loading, long-distance transport, and the capacity of fruits to absorb carbohydrates. In Newhall navel orange, ^{13}C tracing analysis showed that potassium application increased ^{13}C-sucrose accumulation in fruits during the enlargement stage and increased both ^{13}C-sucrose and ^{13}C-glucose contents during the coloration stage, demonstrating that potassium enhances carbon transport from source leaves to sink fruits (Wu et al., 2024). The study further indicated that approximately half of the sugars in citrus fruits originate from transported carbohydrates, and potassium strengthens carbon flow between source and sink tissues by regulating the symplastic loading pathway.

In Nanfeng mandarin, continuous foliar application of K_2SO_4 throughout fruit development increased soluble sugar content, mainly due to enhanced fruit sink strength and sugar transport capacity induced by potassium (Thu et al., 2024). This transport-centered regulatory model is also supported by broader studies in plant nutritional physiology, which demonstrate that potassium is closely associated with the translocation of photosynthetic products from source leaves to sink fruits (Shah et al., 2024; 2025).

4.2 Molecular mechanisms of potassium-induced sugar accumulation

One of the important molecular mechanisms by which potassium promotes sugar accumulation is through enhancing the expression of sugar transport-related genes in leaves and fruits. In Nanfeng mandarin, foliar application of K_2SO_4 increased the expression of CsCWINV-2/6 in the segment membrane tissues and enhanced the expression of CsSUT-1/2 and CsVPP-1/2 in juice sac tissues, linking potassium nutrition with stronger fruit sink activity and sucrose unloading processes (Thu et al., 2024). In Newhall navel orange, potassium enhanced symplastic loading capacity, increased carboxyfluorescein signal intensity, and promoted plasmodesmata density in leaves, indicating that potassium not only affects the expression of sugar transport proteins but also modifies the structural pathways involved in carbohydrate transport (Wu et al., 2024). Sugar storage in citrus fruits also depends on vacuolar transport capacity. A proteomic study by Mao et al. (2024) revealed that tonoplast transporters such as TMT2 and STP7 may participate in regulating sugar accumulation within citrus fruit vacuoles. Related studies in tomato, melon, and magnesium-treated citrus have also demonstrated similar regulatory patterns, showing that potassium or other nutritional treatments can increase the expression of *SUT*, *SWEET*, *VPP*, and vacuolar sugar transporter genes, thereby enhancing sugar import and storage capacity in fruits (Wu et al., 2023; Han et al., 2024; Shah et al., 2025).

Potassium-induced sugar accumulation does not rely solely on sugar transport processes but also involves regulation of carbon metabolism-related gene networks. In Newhall navel orange, potassium increased the activities of key sucrose metabolism enzymes and the expression of related genes in both fruits and leaves, indicating that potassium coordinates carbon metabolism in source tissues with sugar utilization in sink tissues (Wu et al., 2024). Citrus *SPS* genes themselves are regulated by multiple factors, including developmental stage, tissue type, light conditions, hormone levels, and abiotic stresses, suggesting that external nutritional signals, such as potassium, may be integrated into broader sugar signaling regulatory networks (Lu et al., 2024). Further co-expression analysis revealed that WRKY transcription factors, particularly CsWRKY20, may participate in regulating citrus sugar accumulation through the CsSPS-mediated pathway. Studies in grapevine and melon also support this integrated regulatory model, showing that potassium-responsive genes are mainly enriched in pathways related to carbon metabolism, glycolysis/gluconeogenesis, fructose and mannose metabolism, as well as SPS/SUS-mediated regulation (Wang et al., 2024; Shah et al., 2025).

4.3 Relationship between potassium supply and soluble solids content

Adequate potassium supply generally results in a stable increase in total soluble solids (TSS) and soluble sugar content in citrus fruits. In Nanfeng mandarin, six consecutive foliar applications of K_2SO_4 significantly increased fruit TSS and soluble sugar content (Thu et al., 2024). In Cara Cara navel orange, potassium application increased sucrose, fructose, and glucose contents, as well as the ratio of total soluble sugars to citric acid, with the most pronounced improvement observed at an application rate of 0.50 kg potassium per tree (Wu et al., 2021). A meta-analysis conducted by Xu et al. (2024) on Chinese citrus production systems also demonstrated that optimized fertilization management increased TSS by 5.9% and total sugar content by 8.6%. Studies on other fruit crops have shown similar dose–response patterns, indicating that moderate potassium supply generally improves TSS and sugar accumulation more consistently than excessive potassium application (Zhang et al., 2018; Wang et al., 2024).

The effects of potassium on citrus flavor quality are not limited to sugar accumulation but also involve regulation of sugar–acid balance. In Cara Cara navel orange, potassium increased citric acid content by enhancing the activities of citrate synthase and phosphoenolpyruvate carboxylase, while simultaneously increasing the ratio of total soluble sugars to citric acid, thereby improving overall flavor balance (Wu et al., 2021). In contrast, in Nanfeng mandarin, foliar application of K_2SO_4 reduced titratable acidity and increased the TSS:TA ratio, indicating that the effects of potassium on organic acid metabolism are influenced by cultivar characteristics and application strategies (Thu et al., 2024).

Broader integrated studies on citrus have shown that optimized fertilization can reduce titratable acid (TA) and total acid contents while increasing the TSS/TA and TSC/TAC ratios, thereby improving overall fruit quality (Xu et al., 2024). This variation in acidity responses is also consistent with findings from non-citrus crops, where potassium may either promote citric acid synthesis or reduce malic acid and total acid accumulation, depending on plant species, developmental stage, and fertilizer source (Zhang et al., 2018; Wu et al., 2023).

5 Effects of Potassium Fertilization on Citrus Fruit Quality

5.1 Influence on external quality characteristics

Potassium improves the external quality of citrus fruits mainly by promoting fruit enlargement, enhancing peel coloration, and improving market appearance. In Newhall navel orange, combined application of potassium fertilizer and organic fertilizer improved fruit surface color and reduced peel thickness, resulting in a more desirable appearance for consumers (Wen et al., 2021). Shrestha et al. (2025) found that in HLB-tolerant Sugar

Belle citrus grown under sandy soil conditions, foliar potassium application improved peel color and overall fruit quality; potassium nitrate applied in July or from May to July increased fruit size to more than 65 mm. In Page mandarin, potassium-containing foliar nutrient treatments increased fruit diameter and improved peel color parameters, including L*, a*, and b* values, which were consistent with enhanced visual quality (ValizadehKaji and Mohammaei, 2025). In Fremont mandarin, potassium nitrate application promoted fruit enlargement and improved fruit color and appearance, although most internal quality parameters showed limited changes in this experiment (Ülker and Kamiloğlu, 2021).

Potassium also influences peel development and firmness, both of which are important for fruit transportation performance and resistance to physiological disorders. Jiao et al. (2022) reported that potassium application in a citrus hybrid susceptible to fruit cracking increased the ratio of peel firmness to pulp firmness, enhanced potassium, calcium, and nitrogen accumulation in both peel and pulp tissues, and alleviated fruit cracking. The same study system and related citrus research indicate that sufficient potassium supply promotes peel tissue development and structural strengthening, thereby reducing the risk of fruit cracking (Jiao et al., 2022; Shrestha et al., 2025). In Sugar Belle citrus, foliar potassium application before autumn increased peel thickness to approximately 1.15 times that of the control, while combined potassium and boron application improved peel puncture resistance (Shrestha et al., 2025). In sweet lime, foliar application of KNO_3 increased fruit firmness and juice content, which is consistent with the role of potassium in maintaining cell membrane stability and regulating vacuolar osmotic balance (Khan et al., 2025).

However, the effects of potassium on fruit quality are not always consistent. In 'Salustiana' orange, high potassium supply reduced magnesium and calcium accumulation in the flavedo but did not significantly alter peel thickness, external color, firmness, total soluble solids content, or acidity (Manzi et al., 2026).

5.2 Influence on internal quality traits

The most consistent effects of potassium on improving citrus internal quality are mainly reflected in increased total soluble solids (TSS), enhanced soluble sugar accumulation, and improved sugar–acid balance. In Newhall navel orange, an appropriate fruit potassium concentration (approximately 1.5%) promoted sugar accumulation and improved fruit quality, with both field and pot experiments directly demonstrating increased TSS after potassium application (Wu et al., 2024). In Valencia orange, the application of 0.5 kg nitrogen fertilizer and 0.9 kg potassium fertilizer per tree resulted in the highest TSS and TSS/TA ratio, whereas increasing potassium application rates further tended to increase juice acidity (Nguyen and Tai, 2020).

A meta-analysis of 92 studies conducted by Xu et al. (2024) showed that optimized fertilization with an appropriate increase in K_2O input increased fruit TSS by 5.9%, total sugar content by 8.6%, reduced total acidity by 3.4%, and increased the TSS/TA ratio by 14.0%. However, it should be noted that excessive potassium application may negatively affect internal fruit quality in some production systems by increasing acidity and reducing the sugar–acid ratio (Shrestha et al., 2025).

Studies have shown that potassium can improve vitamin C content and influence secondary metabolic processes, although these responses are more complex than changes in TSS. In Newhall orange, combined application of potassium fertilizer and organic fertilizer not only increased TSS and the sugar–acid ratio but also promoted vitamin C accumulation (Wen et al., 2021). In sweet lime, lower concentrations of KNO_3 increased vitamin C content, which may be related to the regulatory effects of potassium on sugar metabolism and ascorbic acid biosynthesis (Khan et al., 2025).

Potassium also alters metabolite composition in citrus peel and pulp, enhancing amino acid biosynthesis in peel tissues and glycoside accumulation in pulp tissues. Jiao et al. (2022) used the fruit-cracking-susceptible citrus hybrid 'Ehime Kashi No. 34' as the experimental material and evaluated three potassium levels. The results showed that potassium treatments increased K, N, and Ca concentrations in both peel and pulp, while improving the peel-to-pulp firmness ratio, photosynthetic rate, and stomatal conductance. Metabolomic analysis identified 59 and 13 differential metabolites in peel and pulp tissues, respectively. Changes in peel metabolism were mainly associated with enhanced amino acid biosynthesis, whereas pulp tissues showed increased accumulation of glycoside-related metabolites. The study suggested that potassium alleviates fruit cracking by coordinating peel mechanical strength with metabolic changes in internal and external tissues, thereby reducing the imbalance between pulp expansion and peel extension during fruit development.

5.3 Potassium optimization for different citrus quality targets

Potassium regulates citrus quality formation mainly through the coordinated regulation of multiple processes, including fruit growth, carbohydrate metabolism, organic acid balance, and peel development (Figure 2). For high-sugar citrus production, current evidence supports an appropriate and timely potassium supply rather than pursuing the maximum potassium application rate. For example, Chen et al. (2026) reported that in semi-arid regions of southwestern China, increasing fertilizer input during stage III enhanced soluble sugar and vitamin C accumulation, while reducing irrigation and increasing fertilizer levels during stage IV also promoted the accumulation of sugars and vitamin *C. Since* commercial citrus maturity largely depends on the ratio of soluble solids to acidity and juice percentage, potassium management aimed at improving sweetness should consider both cultivar characteristics and environmental conditions (Lado et al., 2018; Jiao et al., 2023).

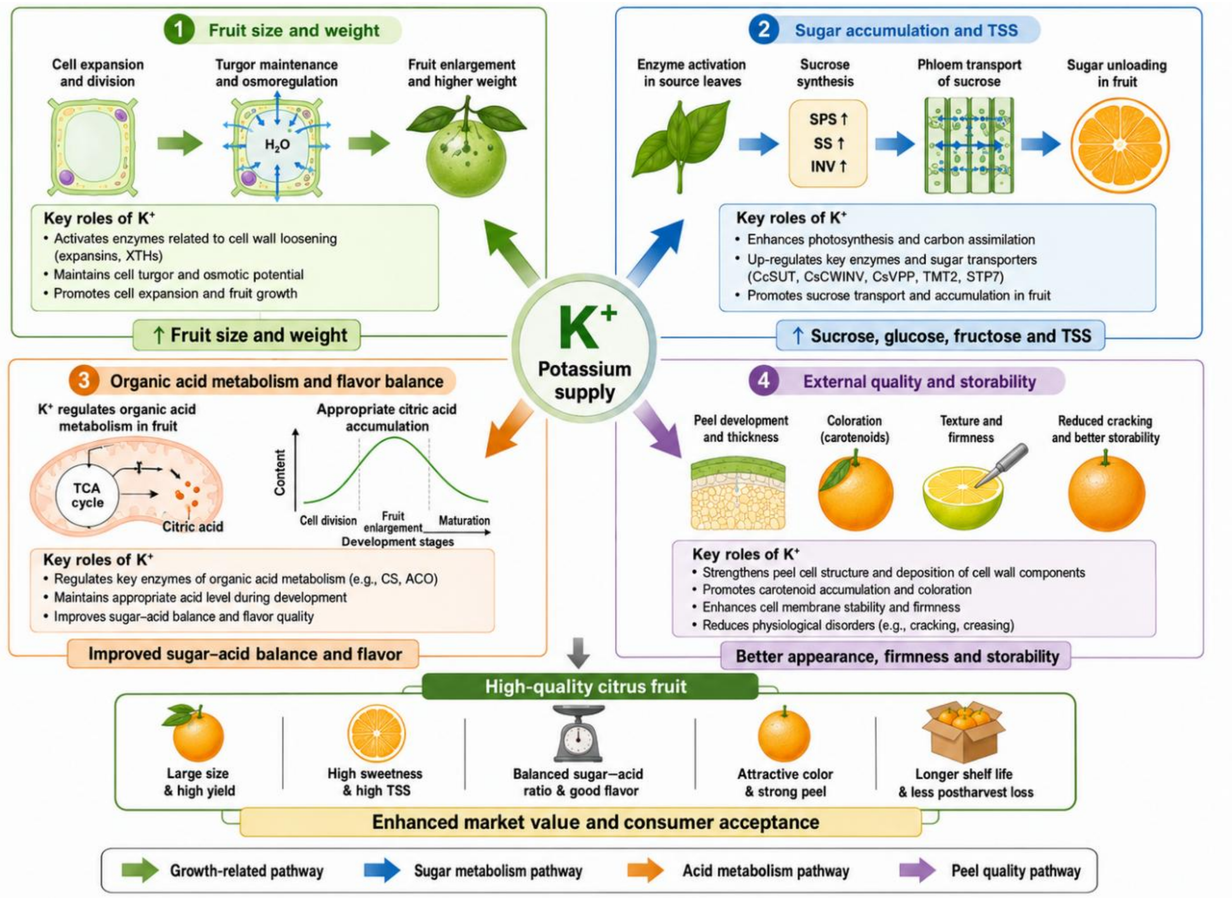

Figure 2 Integrated model of potassium regulation of citrus fruit quality formation

Image caption: The figure summarizes the multi-pathway regulation of citrus fruit quality formation by potassium supply. Adequate potassium availability promotes cell expansion and fruit enlargement, thereby increasing fruit size and weight. Potassium enhances carbon assimilation in source leaves, sucrose synthesis, phloem transport, and sugar unloading processes, resulting in greater accumulation of sucrose, glucose, and fructose and improved total soluble solids content. Meanwhile, potassium regulates organic acid metabolism to optimize sugar-acid balance and flavor development. Potassium also contributes to peel development, coloration, tissue stability, and reduction of physiological disorders such as fruit cracking, ultimately improving commercial value and storage performance of citrus fruits

6 Potassium Fertilization Strategies in Citrus Orchards

6.1 Timing and methods of potassium application

Potassium demand in fruit trees changes throughout different phenological stages, with the highest requirement generally occurring during rapid fruit growth and ripening stages. In citrus production, field studies have similarly demonstrated that flowering and fruit enlargement periods are critical stages for potassium management (Figure 3). Khan and Nabi (2023) used 20-year-old sweet lime (*Citrus limetta*) trees to compare the effects of foliar applications of KCl, K_2SO_4, and KNO_3 on different application dates, including February 15, February 25, March 7, and March 17. The results showed that potassium application on March 17, 13 days after bud emergence, produced the best performance, with an average of 739.52 fruits per tree and a yield of 63.68 kg per tree, while reducing the time required for full bloom to 20 days. Among different potassium sources, the KNO_3 treatment resulted in 808.75 fruits per tree, a yield of 69.48 kg per tree, and an average fruit weight of 85.64 g. The study indicated that potassium application after bud emergence in spring was more effective than application during the late winter dormancy period, suggesting that the period from spring bud development to flowering represents a critical window influencing flowering progression, fruit number, and yield formation.

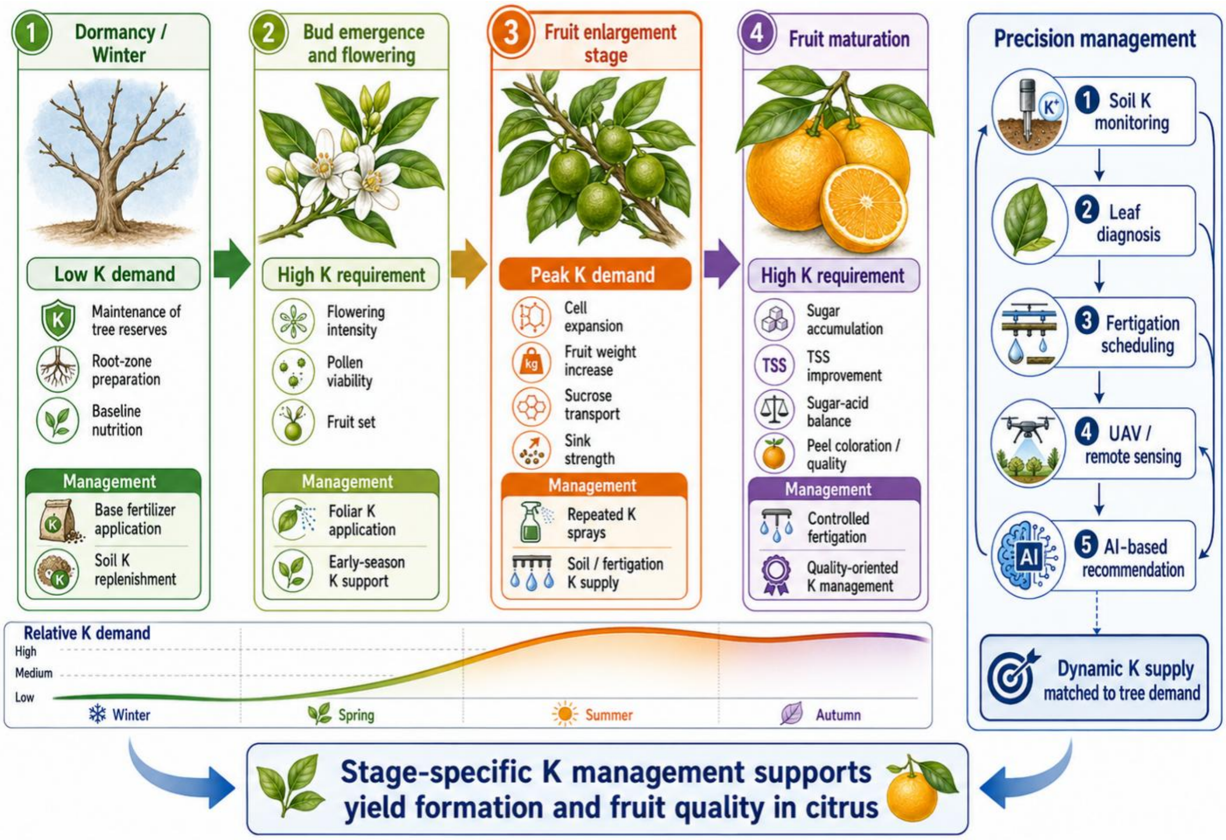

Figure 3 Stage-specific potassium demand and fertilization strategies during citrus development

Image caption: The figure presents stage-specific potassium requirements and fertilization strategies throughout citrus development. Potassium demand is relatively low during dormancy but increases during bud emergence, flowering, and fruit set. The fruit enlargement stage represents the peak potassium demand period, during which potassium supports cell expansion, fruit weight formation, and assimilate transport. During maturation, adequate potassium supply promotes sugar accumulation and fruit quality improvement. Integration of soil monitoring, leaf diagnosis, fertigation, remote sensing, and intelligent management enables precise potassium regulation according to tree demand

In sweet orange, two to three foliar sprays applied around late April, May, and August improved yield and fruit size, with 4% KNO_3 showing the best performance among the tested foliar fertilization treatments. In Washington navel orange, five foliar potassium applications from March to July improved leaf nutrient status, yield, and fruit quality, indicating that a staged potassium supply strategy during early reproductive growth and fruit development can provide positive effects (Al-Sabbagh and El-Gioushy, 2024).

Soil potassium application remains the primary potassium management strategy in orchards because it can continuously support root uptake throughout the growing season. However, citrus studies have shown that foliar potassium application plays an important complementary role when soil conditions limit nutrient availability. Ahmad et al. (2022) reported that in alkaline or calcareous citrus soils, soil fertilization alone often fails to achieve optimal leaf nutrient levels, making foliar fertilization an effective rapid correction method. Field comparisons in citrus have demonstrated that both basal soil potassium application and foliar potassium spraying promote plant growth and improve fruit quality. However, foliar application generally produces faster or more pronounced quality responses, whereas soil potassium application is more effective for increasing fruit weight and maintaining long-term tree nutrient supply (Tahir et al., 2023).

Fertigation provides a more precise approach for potassium management by matching potassium supply with seasonal nutrient requirements and root-zone environmental conditions. Based on lysimeter experiments in citrus, Zayani et al. (2024) found that nutrient concentrations in soil solutions varied substantially with irrigation amount, fertilizer input, and soil conditions, indicating that data-driven fertigation management based on real-time monitoring has advantages over fixed fertilization schedules.

6.2 Optimization of potassium application rates and nutrient balance

When potassium deficiency occurs in citrus orchards, increasing potassium supply generally improves plant performance. However, this response is not always linear, and excessive potassium application may reduce fertilizer use efficiency or cause nutrient imbalances. A meta-analysis of 92 citrus fertilization studies conducted by Xu et al. (2024) showed that optimized fertilization strategies increased K_2O application by an average of 6.6% compared with conventional fertilization practices, while simultaneously improving fertilizer productivity, yield, individual fruit weight, total soluble solids content, sugar content, and the sugar–acid ratio. The greatest production benefits were mainly achieved through integrated nutrient management, particularly strategies involving optimized N-P-K ratios combined with the application of secondary and micronutrients.

Experiments with different potassium application rates have also supported this pattern. In ‘Salustiana’ orange, low, medium, and high annual potassium application rates altered potassium concentrations in leaves and flavedo tissues, but high potassium supply did not further improve the measured fruit quality parameters (Manzi et al., 2026). In Newhall navel orange, moderate application of organic fertilizer combined with potassium sulfate produced the best fruit quality performance, with a recommended K_2SO_4 application rate of 1.15-1.20 kg per tree under the tested soil conditions (Wen et al., 2021).

For a long time, citrus nutrient management recommendations have suggested that potassium supply should be maintained at a level close to nitrogen supply to achieve high yield and superior fruit quality (Khan and Nabi, 2023). However, excessive potassium availability may inhibit calcium and magnesium uptake. In hydroponically grown lemon, high potassium concentrations reduced the overall uptake of phosphorus, calcium, magnesium, boron, manganese, and zinc, with these effects being particularly evident at 6 mM potassium concentration (Papadakis et al., 2023). Brital et al. (2024) further found in Valencia orange orchards in Morocco that potassium-magnesium antagonism could still occur in leaves even when soil potassium availability was sufficient, indicating that soil potassium content alone cannot accurately reflect the nutritional balance status of citrus trees.

6.3 Precision potassium management

In recent years, commercial orchard data analysis has provided more quantitative evidence for potassium management. For example, Lima Neto et al. (2025) used boundary line analysis to estimate the optimal soil potassium concentration range for citrus orchards as 161.4-326.0 mg/dm^3 and the suitable leaf potassium concentration range as 7.8-11.3 g/kg. The study also established optimal ranges for other nutrients, including nitrogen, calcium, and magnesium. Monitoring studies in Clementine mandarin orchards in Morocco similarly revealed substantial variations in soil solution nutrient availability and leaf nutrient composition among different fields and phenological stages, highlighting the importance of continuous leaf nutrient diagnosis (Zayani et al., 2024).

Precision potassium management is increasingly moving toward data-driven approaches. For example, unmanned aerial vehicle (UAV)-based multispectral imaging combined with machine learning techniques can accurately estimate major nutrient concentrations, including potassium, in citrus trees and generate spatial nutrient distribution maps for commercial orchards, providing a basis for site-specific fertilization management (Costa et al., 2022). More broadly, intelligent fertilizer recommendation systems integrating artificial intelligence (AI), the Internet of Things (IoT), and interpretable models demonstrate that real-time soil and climate data can support more accurate and explainable fertilization decisions (Venkateswara and Padmanaban, 2025). Studies in other fruit crops have also confirmed the practical value of adjusting potassium fertigation programs according to actual crop load and using machine vision technologies to optimize potassium demand prediction. These approaches may provide useful references for citrus orchards, where fruit load often varies considerably among different production years (Kuzin et al., 2020).

7 Integrated Potassium Management for Citrus Orchards

7.1 Coordination of potassium with other nutrient management

Potassium management should be considered as a component of an integrated nutrient management system because fruit growth and quality formation depend more on the coordinated uptake of nitrogen, phosphorus, and potassium rather than potassium supply alone. Ma et al. (2022) reported that drip fertigation improved fruit total soluble solids (TSS), titratable acidity (TA), and vitamin C content while increasing nitrogen, phosphorus, and potassium accumulation in fruits. The underlying mechanism was mainly attributed to nitrogen promoting sugar synthesis through enhanced photosynthesis, whereas phosphorus and potassium contributed more directly to sugar accumulation and regulation of the sugar-acid ratio. Field monitoring in Clementine mandarin orchards in Morocco similarly showed that optimized fertilization programs required increased nitrogen and potassium inputs compared with conventional local practices; however, monthly leaf nutrient diagnosis indicated that the major limitation was not simply insufficient annual nutrient supply but rather an inappropriate temporal distribution of nitrogen and potassium availability (Zayani et al., 2024). In Washington navel orange, repeated foliar applications of KNO_3 improved leaf nutritional status, productivity, and fruit quality, suggesting that potassium can be combined with nitrogen through a single fertilizer source during periods of high canopy nutrient demand (Al-Sabbagh and El-Gioushy, 2024).

Interactions among potassium, calcium, and magnesium are also highly important, as the balance of cation supply influences peel integrity, root health, and fruit development. For example, in a citrus hybrid susceptible to fruit cracking, potassium application increased calcium, nitrogen, and potassium concentrations in both peel and pulp tissues and improved the peel-to-pulp firmness ratio, which was associated with reduced fruit cracking incidence (Jiao et al., 2022). A field-scale analysis of fruit cracking in Bingtang sweet orange by Shi et al. (2025) further demonstrated that soil calcium, potassium, and magnesium were important factors affecting cracking severity. Fruit cracking rate was negatively correlated with soil calcium and potassium concentrations but positively correlated with soil magnesium content.

However, excessive potassium supply may aggravate cation imbalance. In ‘Salustiana’ orange, high potassium treatments increased potassium accumulation in leaves and flavedo tissues but reduced calcium and magnesium accumulation in fruit tissues (Stagno et al., 2024). Such nutrient imbalance is relatively common in commercial production. A survey in southwestern China found that severe magnesium deficiency was closely associated with excessive nitrogen and potassium fertilization. Optimized management practices involving magnesium supplementation and reduced N-P-K inputs improved yield, fruit quality, nutrient use efficiency, and economic returns (Wang et al., 2022).

7.2 Integration of potassium fertilization with irrigation management

Potassium use efficiency is highly dependent on soil water conditions. In citrus orchards, potassium is prone to leaching losses, while water deficits and irregular rainfall patterns can alter potassium uptake processes and influence the occurrence of physiological disorders in fruits. A two-year citrus field experiment showed that maintaining 70% soil moisture combined with alginate oligosaccharide application increased yield by 11.93%-13.31%, total soluble sugar content by 15.16%-17.47%, sucrose content by 18.92%-20.81%, fruit potassium concentration by 51.09%-62.21%, and water use efficiency by 12.01%-13.34%. This treatment performed better than both higher and lower irrigation regimes (Li et al., 2024). The same treatment also enhanced net photosynthetic rate and root growth, increased available potassium content in the 0-20 cm soil layer, and reduced potassium movement into deeper soil layers, indicating that suitable soil moisture conditions improve potassium retention in soil and enhance plant potassium utilization.

Similar conclusions were reported by Stagno et al. (2024) in a deficit irrigation study on orange trees. Water-saving irrigation strategies reduced irrigation volume by 25%-49% without reducing yield, while improving water use efficiency and maintaining generally adequate mineral nutrition levels. However, leaf potassium concentrations under these treatments were often below the recommended range. These irrigation regimes also increased fruit vitamin C content, pulp coloration, and sugar concentration, suggesting that moderate water regulation can work synergistically with potassium management to improve fruit quality.

In citrus production, drip fertigation improves fruit TSS and juice percentage, enhances nitrogen, phosphorus, and potassium uptake, and reduces nitrogen and potassium losses through leaching and runoff compared with conventional fertilizer application methods such as broadcasting, hole application, or irrigation-based fertilizer delivery. Ma et al. (2022) found that drip fertigation could still promote citrus growth and development even with a 60% reduction in fertilizer input, indicating substantial potential for improving potassium use efficiency while reducing total fertilizer consumption. Monitoring results from mobile lysimeters in Moroccan citrus orchards further demonstrated that nutrient concentrations in soil solutions fluctuate significantly with irrigation amount, fertilizer input, and soil conditions. Therefore, water and fertilizer management based on real-time monitoring is more effective than fixed fertilization schedules (Zayani et al., 2024).

7.3 Application of precision potassium management in citrus orchards

Precision potassium management requires integration of soil testing and leaf nutrient diagnosis. Ahmad et al. (2022) conducted field investigations in calcareous citrus soils and found that soil potassium concentrations at different soil depths were generally at moderate levels, while deficiencies of nitrogen and micronutrients in leaves were widespread. This indicated that soil fertilization alone may not fully satisfy tree nutrient requirements, and foliar fertilization should be incorporated to improve orchard nutritional status. In recent years, boundary line analysis based on commercial orchard data has provided more accurate reference ranges. The study estimated that suitable potassium concentrations for citrus orchards were 161.4-326.0 mg/dm^3 in soil and 7.8-11.3 g/kg in leaves, which can serve as practical guidelines for precision potassium fertilization recommendations (Lima Neto et al., 2025).

Precision fertilization strategies also need to be adjusted according to cultivar characteristics and developmental stages. In Clementine mandarin orchards, the fertilization requirements of the cultivars ‘Nour’, ‘Orogrande’, and ‘Nules’ differed, and monthly leaf nutrient diagnosis indicated that potassium should be supplemented in a timely manner before and during fruit growth and ripening stages (Zayani et al., 2024). In ‘Magallanes’ pomelo, key growth periods were mainly concentrated in May and August, while April represented the peak period for flowering and fruit set. The two months after fruit set were identified as a critical developmental stage, suggesting that potassium supply should be synchronized with these key physiological periods (Magbalot-Fernandez and Guzman, 2019). This study further showed that potassium application rates recommended based on soil analysis promoted canopy growth, whereas higher potassium inputs further increased flowering intensity, fruit set, fruit number, individual fruit weight, and yield, indicating that the optimal potassium rate depends on specific production objectives.

Studies on lemon and Kinnow mandarin further demonstrate that fertilization methods and treatment combinations should be matched with production goals. Foliar application of NG-K was more effective than basal application of sulfate of potash (SOP) in improving sugar accumulation and juice quality parameters (Tahir et al., 2023). Among different management strategies, application of a salicylic acid (SA) + potassium (K) + zinc (Zn) combination across three growth stages showed the most consistent effects in reducing fruit drop and improving juice quality across multiple locations (Anwar et al., 2022).

8 Advances and Future Trends in Citrus Potassium Management

Potassium is an essential nutrient that influences citrus tree growth and fruit quality formation, playing important roles in photosynthetic carbon assimilation, assimilate transport, fruit development, and quality regulation during maturation. Current studies indicate that appropriate potassium supply can improve leaf photosynthetic capacity, enhance material transport between source and sink tissues, and promote fruit enlargement and sugar accumulation. The effectiveness of potassium management is affected by multiple factors, including cultivar characteristics, rootstock type, soil conditions, water availability, and fertilization practices. Developing potassium management strategies adapted to different production conditions is therefore an important basis for achieving high-quality and efficient citrus production.

The regulatory effects of potassium on citrus fruit development are mainly associated with improved cellular expansion conditions, enhanced fruit growth, and strengthened nutrient supply capacity of the tree. Potassium demand is generally higher during rapid fruit growth and maturation stages, and timely potassium supplementation can improve fruit weight and marketability. Different citrus groups show distinct responses to potassium supply, with some cultivars exhibiting stronger effects on fruit enlargement, whereas others respond more significantly in terms of sugar accumulation and flavor improvement. In practical production, fertilization strategies should be adjusted according to cultivar characteristics and developmental stages to improve the synchronization between potassium supply and tree nutrient requirements.

The role of potassium in fruit quality formation is closely related to carbon metabolism and sugar transport processes. An appropriate potassium level promotes the translocation of photosynthetic products to fruits, regulates the activities of sucrose metabolism-related enzymes, and affects sugar transport processes, ultimately improving total soluble solids content and sugar–acid balance. However, excessive potassium supply may interfere with the uptake of calcium, magnesium, and other mineral elements, resulting in nutrient imbalance and reduced fertilizer use efficiency. Therefore, maintaining a balanced relationship between potassium and other mineral nutrients is essential for producing high-quality citrus fruits, and excessive potassium input should be avoided.

Future research should further improve precision potassium management systems in citrus orchards. Potassium requirements under different cultivar–rootstock combinations and ecological regions need to be validated through long-term field experiments, combined with leaf nutrient diagnosis and soil nutrient monitoring to establish more reliable evaluation indicators. The molecular basis underlying potassium regulation of fruit quality formation also requires further investigation, particularly regarding the interactions between potassium signaling, sugar metabolism networks, hormonal regulation, and fruit ripening processes.

With the development of fertigation, remote sensing, and smart agriculture technologies, citrus potassium management is expected to become increasingly dynamic and precise. Integrating soil, plant, and environmental information for nutrient demand prediction can improve potassium use efficiency and reduce resource losses. Future studies should strengthen the coordination of potassium management with irrigation, nitrogen and phosphorus nutrition, and micronutrient regulation, aiming to establish a more efficient, stable, and sustainable citrus nutrient management system and provide theoretical support and technical guidance for the development of modern citrus production.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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