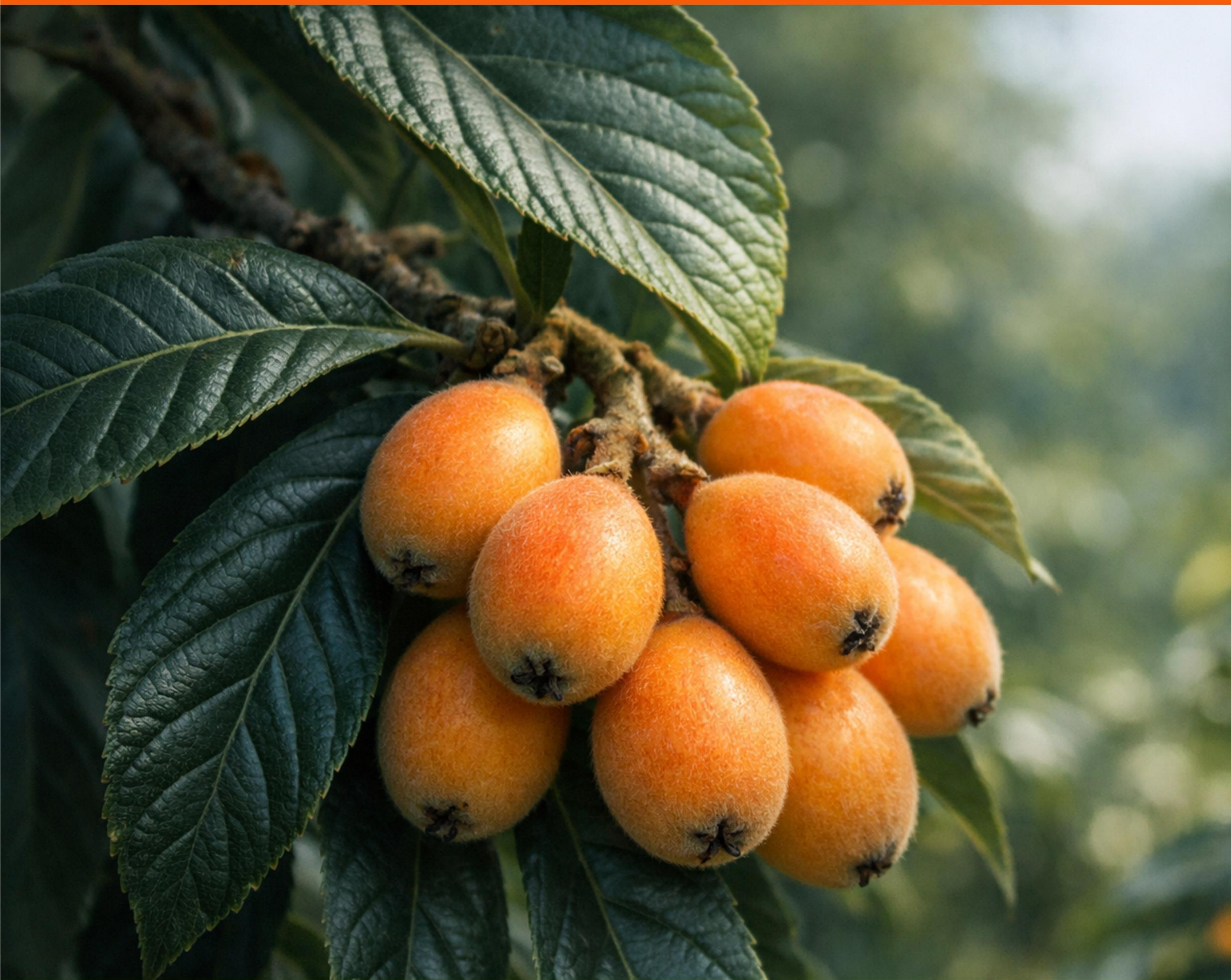
International Journal of Horticulture

Loquat (*Eriobotrya japonica*)

Vol.16 No.2 2026



https://hortherbpublisher.com/index.php/ijh

ISSN 1927-5803

2026
02

Publisher
HortHerb Publisher

Edited by
Editorial Team of International Journal of Horticulture
Email: edit@ijh.hortherbpublisher.com
Website: http://hortherbpublisher.com/index.php/ijh

Address:
11388 Stevenston Hwy,
PO Box 96016,
Richmond, V7A 5J5, British Columbia
Canada

International Journal of Horticulture (ISSN 1927-5803) is an open access, peer reviewed journal published online by HortHerb Publisher.

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International Journal of Horticulture (online), 2026, Vol. 16, No.2
ISSN 1927-5803
http://hortherbpublisher.com/index.php/ijh

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Profitability and Constraints of French Bean Production in Kalikot District of Nepal

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0006
Received: 15 Dec., 2025
Accepted: 10 Feb., 2026
Published: 23 Mar., 2026

Preferred citation for this article:
Panta S., Pandey S., Dhungana P., Pokhrel L., Pant S., and Regmi S., 2026, Profitability and constraints of French bean production in Kalikot District of Nepal, International Journal of Horticulture, 16(2): 68-76 (doi: 10.5376/ijh.2026.16.0006)

Abstract French bean cultivation is an important agricultural enterprise in the high hills of Nepal; however, farmers face substantial production and marketing constraints. A study was conducted in the Kalikot district to assess the profitability and key constraints of French bean production. Data were collected through household surveys from 100 bean-growing households selected through proportionate stratified random sampling across different local levels in the Kalikot district. The results revealed an average productivity of 76.10 kg per ropani, with 59.5% of the total production marketed and the remainder used for household consumption and seed purposes. The average cost of production was NRs 11,350 per ropani, while gross returns amounted to NRs 15,372, yielding a gross margin of NRs 4,062 and a benefit cost ratio of 1.35, indicating that French bean cultivation is economically profitable. The independent sample t-test results showed significantly higher productivity among trained, literate farmers, and farmers who were members of cooperatives. Multiple regression analysis ($R^2 = 0.7588$, $p < 0.001$) identified cultivated area, irrigated land, annual income, and training as significant determinants of total bean production. Major constraints in production include high disease and pest incidence (0.856), particularly anthracnose (0.880) and aphids (0.853), while the key marketing challenge was unorganized marketing systems (0.748). The study concludes that targeted interventions in training, disease and pest management, and market organization can substantially enhance the productivity, profitability, and sustainability of French bean production in Kalikot, Nepal.

Keywords French bean (*Phaseolus vulgaris* L.); Benefit cost ratio; High hills; Production economics; Smallholder farming

1 Introduction

Agriculture is the backbone of the Nepalese economy, employing approximately 60% of the population and contributing nearly 23.8% of the Gross Domestic Product (GDP). Most people depend on agriculture for their livelihoods, particularly in rural areas (MOALD, 2024). Nepal is gradually shifting from subsistence farming to commercial agriculture to reduce poverty, enhance food security, and promote economic growth (Bist et al., 2025). Pulses play a vital role as an important source of nutrition and as a cash crop that plays a significant role in enhancing household income in rural areas of Nepal (Ghimire et al., 2022). Pulses, such as lentils, beans, peas, and other grain legumes, are of major importance for both human nutrition and sustainable farming, as they form a key component of the Nepalese diet by providing essential proteins and micronutrients and contributing to soil health through their capacity for biological nitrogen fixation (Dhakal, 2020; Basnet et al., 2022).

French bean (*Phaseolus vulgaris* L.), also known as common bean, is an herbaceous annual plant in the Fabaceae family. It exhibits bush (20-60 cm tall) or pole (2-3 m vines) growth habits, with trifoliate leaves (6-15 cm long leaflets) and white-to-purple flowers producing flat pods with 5-12 seeds. Roots are taproot systems with nodules for nitrogen fixation. Stems are herbaceous and angular; pods are straight or sickle-shaped, 8-20 cm long, containing kidney-shaped seeds (1-2 cm) (Bharti et al., 2023; Sinkovič et al., 2024).

French beans (*Phaseolus vulgaris* L.) are an important legume crop in Nepal, particularly in the Karnali region, where they provide a crucial source of income and nutrition for local farmers (Luitel et al., 2019; Mira, 2021). It is extensively cultivated from the Terai to the high hills, occupying approximately 10,529 hectares with a total production of 15,550 metric tonnes and an average productivity of 1,477 kg/ha. Among the commonly grown genotypes, PB0001, KBL-5, and KBL-8 exhibit a bush growth habit, whereas PB0002, PB0048, and other KBL genotypes are of the trailing type. French beans or common beans, which are recognized for their high protein content and wide adaptability, are a major legume crop in the mid-hill and mountainous regions of Nepal (Chhetri and Bhatta, 2017; Luitel et al., 2021). The beans grown in the Karnali zone of Nepal are known as Jumli simi, which are traditional high-altitude landraces of French beans. (Prasad et al., 2016). Mixed bean cultivation has traditionally been an integral practice in mountain farming systems, although it is gradually being replaced by monocropping (Joshi et al., 2025). The three-year average results showed that the Chaumase genotype produced the highest green pod yield (35.0 t/ha), followed by Trishuli (28.0 t/ha), WP Con Bean (24.6 t/ha), and White OP (22.9 t/ha). Similarly, in terms of seed yield, Chaumase and Trishuli (2.1 t/ha each) performed best, while Dhankute Chirrke (1.44 t/ha) and White OP (1.09 t/ha) were found to be promising genotypes for seed production (Kalauni et al., 2019).

In the Tilagufa municipality of Kalikot, French beans are traditionally produced on a small scale, with limited access to quality seeds, irrigation, fertilizers, and pesticides, resulting in high production costs. Pests and diseases were major challenges in production and limited market information is the major marketing problem. Despite low yields due to these constraints, French bean cultivation is economically important in the Karnali region, offering significant income opportunities and potential to improve food security and rural livelihoods (Adhikari et al., 2024).

2 Materials and Methods

2.1 Study area and sample size

For this study, the Kalikot district was purposively selected because it is one of the most French bean producing districts in the high hills of the Karnali region. A total of 100 farmers were chosen from a population of 3,022 for data collection using proportionate stratified random sampling across the different local levels. A field survey was conducted in February 2025 to collect primary data from farmers through semi-structured questionnaires, focus group discussions, and key informant interviews, while secondary data were obtained from various sources. Data analysis was performed using Microsoft Excel 10 and STATA V12. Descriptive statistics such as means and frequencies, as well as gross margin, profitability index, multiple linear regression, independent sample t-tests, and severity indices for major bean production problems were computed.

2.2 Gross margin and profitability index analysis

Gross margin is the difference between the Gross return (GR) and the Total Variable Cost (TVC). It is a useful planning tool in situations where fixed capital is a negligible portion of the farming enterprise in the case of small-scale subsistence agriculture (Olukosi and Erhabor, 1988). Gross margin was calculated as follows:

Gross margin (GM) = Gross return (GR) – Total variable cost (TVC)
Net profit = Gross margin (Rs.) – Fixed cost (Rs.)

Where, Gross return (Rs.) = Price of French beans (Rs. /kg) × total quantity sold (kg);
Total variable cost (Rs.) = Summation of the cost of all variable inputs;
Profitability index = Net farm Income / Total variable cost (NFI/TVC)

2.3 Indexing

Scaling techniques provide the direction and extremity attitude of the respondent towards any proposition (Miah, 1993). The problems faced by the bean farmers in the study area were ranked by using a scaling technique comparing the intensity of different levels of using scale values 1, (1-1/n), (1- 2/n), (1-3/n) and so on:

$$I = \sum S_i * f_i / N$$

Where, I = index 0 < I <1; I = index value (ranging from 0 to 1); S_i = scale value for the i^{th} severity category; f_i = frequency of responses in the i^{th} severity category; N = total number of respondents (= ∑fi)

3 Results and Analysis

3.1 Descriptive statistics of household and income variables

The results show that bean-producing households had an average family size of 6.15 members (Table 1). On average, 2.42 members per household were actively involved in agriculture, indicating reliance on family labor alongside hired labor. The mean age of the farmers was 43.02 years, suggesting that production is mainly managed by middle-aged, experienced farmers. The average annual household income was NPR 1,041,800, of which agriculture contributed NPR 624,200, highlighting farming as a major income source.

Table 1 Descriptive statistics of household and income variables

Variable	Unit	Mean	SD	Min	Max
Family members	Number of members	6.15	1.81	2	10
Active members involved in agriculture	Number of members	2.42	1.14	1	5
Age	Years	43.02	6.03	29	67
Total income	NPR	1,041,800	499,176	160,000	4,500,000
Agriculture income	NPR	624,200	563,677	60,000	3,200,000

Note: SD = Standard deviation; Min = Minimum; Max = Maximum; NPR = Nepalese Rupee

3.2 Cost of production of French bean

The results reveals that the variable costs accounted for almost the entire cost of cultivation (99.64%), indicating a labor- and input-intensive production system. Among the variable cost components, labor cost was the dominant expense constituting 45.32% of the total cost (Table 2). This was followed by expenditures on organic manure (24.71%), land preparation (14.94%), and seeds (14.66%), suggesting that soil fertility management and field operations also require substantial investment. It emphasizes that production costs are largely driven by variable inputs, particularly labor, and that any increase in labor efficiency or access to improved inputs could reduce the cost of cultivation and improve farm profitability

Table 2 Cost of production of French bean per ropani

Particulars	Cost (NRs.)	Percentage (%) of total cost
Variable cost		
Seed	1,665	14.66
Organic manure	2,805	24.71
Land preparation	1,696	14.94
Labour cost	5,144	45.32
Total variable cost (A)	11,310	99.64
Fixed cost		
Land tax	40	0.36
Total fixed cost (B)	40	0.36
Total cost (A+B)	11,350	100

3.3 Price of French beans

It reveals that the average farmgate price of French beans was NRs. 202/kg while the market price was NRs. 260/kg, resulting in a price margin of NRs. 58/kg (Table 3). Price variability was greater at the farm level than in the market, highlighting challenges in price stability and the need for better market access and information for the farmers.

Table 3 Price of French beans

Price	Observations	Mean	Std. Dev.
Farmgate price (Rs)	100	202	15
Market price (Rs)	100	260	7.5

3.4 Production and productivity of French beans

It reveals that the average productivity of French beans in the study area was 76.10 kg per ropani, indicating a moderate yield under the prevailing traditional production practices (Table 4). The average annual production per household was 429.7 kg, which reflects the small-scale nature of bean cultivation and limited land allocation to the crop. Households consumed an average of 132 kg per year out of the total production, which highlights the importance of French beans as a key component of household nutrition and food security. The marketed surplus was 255.7 kg per household per year, with a monetary value of NRs 51,550, which represents a substantial share of total production, indicating that the French bean is not only grown for subsistence but also serves as an important cash crop.

Table 4 Production and productivity of French beans

Variables	Value
Productivity	76.10 kg/ropani
Average total production from household	429.7 kg/year
Average family consumption	132 kg/year
Average stored for seed	42 kg/year
Marketed Surplus	255.7 kg/year

3.5 Gross margin, net margin and benefit cost ratio

The results show that average gross return was NRs. 15,372.2 per ropani, resulting in a gross margin of NRs. 4,062.2. After deducting fixed costs, the net margin was NRs. 4,022.2 per ropani, indicating that French bean cultivation is financially viable under the existing production conditions in the study area. The B:C ratio of 1.35 further confirms profitability, as returns exceeded costs by 35 percent (Table 5).

Table 5 Gross margin, net margin and benefit cost ratio

Variables	Average value NRs/ropani
Total cost	11,350
Total fixed cost	40
Total variable cost	11,310
Gross returns	15,372.2
Gross margin	4,062.2
Net margin	4,022.2
B:C ratio	1.35

3.6 Mean yield comparison of farmers

The results show that French bean productivity was significantly higher among farmers who received training and those who were members of cooperatives, indicating the positive role of institutional support and access to information (Table 6). Literate farmers also achieved markedly higher yields than illiterate farmers, highlighting the importance of education in improving farm productivity. In contrast, male farmers recorded slightly higher yields than female farmers, but the difference was not statistically significant. Overall, training, cooperative membership, and literacy emerged as key factors influencing french bean productivity in the study area.

3.7 Factors affecting production of French bean in the study area

Table 7 reveals that multiple regression model was statistically significant ($F = 28.00$, $p < 0.001$), indicating that the explanatory variables jointly influenced the bean production. The model explained approximately 75.9% of the variation in production ($R^2 = 0.758,8$), and the high adjusted R^2 (0.731,7) confirmed strong explanatory power even after accounting for the number of predictors. With 100 observations and a relatively low Root MSE (229.25), the model demonstrated good statistical reliability and robustness.

Table 6 Mean yield comparision of farmers by independent sample t-test

S. N	Categories	N	Mean (kg/ropani)	df	*p*-value	t-value
1	Training received	51	79.27	98	< 0.001	4.66***
2	Training not received	49	69.48	-	-	-
3	Cooperative member	64	76.62	98	0.006	2.80***
4	Non member	36	70.11	-	-	-
5	Male	73	75.05	98	0.270	1.11
6	Female	27	72.17	-	-	-
7	Literate	65	78.21	98	< 0.001	5.22***
8	Illiterate	35	66.97	-	-	-

Note: *** represents significance at 1%

Table 7 Summary statistics of the multiple regression model for bean production (N = 100)

Statistic	Value
Number of observations (N)	100
F-value	28.00***
R^2	0.758
Adjusted R^2	0.731
Root Mean Square Error	229.25
Significance level	$p < 0.001$

The regression results show that total cultivated area, irrigated land, training, and annual income had a significant positive effect on bean production, indicating the importance of resource availability and capacity building (Table 8). In contrast, education, cooperative membership, experience, gender, age, and family size did not significantly influence the total production of French beans in the study area. It was found that production was mainly driven by access to land, irrigation, financial resources, and training rather than by socio-demographic characteristics.

Table 8 Factors affecting production of French bean in the study area

S. N	Variable	Coefficient B	Standard error	t-value	*p*-value
1	Education	-5.94	33.43	-0.18	0.859
2	Total area	37.97	4.79	7.93	< 0.001***
3	Irrigated land	20.44	6.90	2.96	0.004***
4	Cooperative	-25.84	62.88	-0.41	0.682
5	Experience	-1.24	3.86	-0.32	0.749
6	Gender	-51.89	53.84	-0.96	0.338
7	Age	-2.70	3.91	-0.69	0.492
8	Family size	11.35	19.75	0.57	0.567
9	Training	129.11	57.37	2.25	0.027**
10	Annual income	19.37	6.03	3.21	0.002***
11	Constant	-288.52	309.16	-0.93	0.353

Note: ** and *** represents significance at 5% and 1% respectively

3.8 Level of satisfaction of farmers

It reveals that most farmers (40%) were moderately satisfied with their bean production, while 26% were not satisfied, 21% were neutral, and only 13% were strongly satisfied, indicating moderate overall satisfaction with room for improvement in addressing their concerns and enhancing overall satisfaction (Table 9).

Table 9 Satisfaction level of farmers

Level of satisfaction	Frequency	Percentage (%)
Not satisfied	26	26
Neutral	21	21
Moderately satisfied	40	40
Strongly satisfied	13	13

3.9 Severity of constraints

3.9.1 Severity of production problems in the study area

The major constraints in French bean production were ranked based on weighted scores in Table 10, where disease and pest incidence were found to be the most severe (0.856), followed by irrigation issues (0.820).

Table 10 Severity of production problems in the study area

Factor	Weighted score	Rank
Disease/Pest	0.856	1
Irrigation	0.820	2
Lesser alternatives for organic agriculture	0.470	3
Lack of technical knowledge	0.440	4
Labor shortage	0.418	5

3.9.2 Severity of bean pests in the study area

The results reveal that aphids and pod borer are the most severe insect pests of French beans, followed by leaf miners, with weevils and Mexican bean beetles posing lesser threats, which suggests that pest management should prioritize the first two for effective yield protection (Table 11).

Table 11 Severity of bean pests in the study area

Factor	Weighted score	Rank
Aphids	0.853	1
Pod borer	0.829	2
Leaf miner	0.582	3
Weevils	0.419	4
Mexican bean beetle	0.388	5

3.9.3 Severity of major diseases of beans in the study area

Table 12 reveals that anthracnose was the most severe (0.880), followed by rust (0.764) and root rot (0.630). Powdery mildew (0.404) and mosaic virus (0.294) are comparatively less serious, which suggests that disease management should primarily focus on anthracnose, rust, and root rot to reduce crop losses.

Table 12 Severity of major diseases of beans in the study area

Factor	Weighted score	Rank
Anthracnose of bean	0.880	1
Rust of bean	0.764	2
Root rot	0.630	3
Powdery mildew	0.404	4
Mosaic virus	0.294	5

3.9.4 Severity of major marketing problems in the study area

The results show that the major marketing constraints for French beans are unorganized marketing (0.748), followed by limited storage facilities (0.636) and seasonal oversupply (0.634), which indicates that improving market organization, storage, and information access could enhance farmer income and reduce post-harvest losses (Table 13).

Table 13 Severity of major marketing problems in the study area

Factor	Weighted score	Rank
Unorganized Marketing	0.748	1
Dependence on intermediaries	0.636	2
Seasonal oversupply	0.634	3
High Transportation cost	0.542	4
Limited market information	0.474	5

4 Discussion

The bean producing household size in the study area is higher than the average of the country, which is 4.37 (National Statistics Office, 2021), indicating relatively large family units, which is common in rural Nepal. Such family sizes can be advantageous for labor-intensive agricultural activities, as family labor remains a primary input in smallholder farming systems (Bhandari and Ghimire, 2013). The wide range of annual income values of farmers reflects considerable variation among households in terms of resource access and production capacity (Gáfaro et al., 2025).

The human labor constitutes 45.32% of total cost of production highlighting the heavy reliance on manual labor in bean cultivation which is slightly higher than 41.14% reported by Tongbram et al. (2021). Joshi et al. (2022) reported that the total cost of production of Kidney beans per ropani was NRs 21,815 in Darchula district of Nepal, while Tongbram et al. (2021) reported the cost of cultivation of French beans is INR 238,894 per hectare in Manipur, Northeast India. Tongbram et al. (2021) reported a B:C ratio of 1.9,6 and Joshi et al. (2022) reported a B:C ratio of 1.29.

Farmer training programs improve knowledge, awareness, adoption of technologies, efficiency, and overall farm productivity through extension services (Baral and Gyawali, 2024). Cooperatives in Nepal enhance vegetable productivity for smallholders by improving input access, extension services, market linkages, and technology adoption, thereby serving as economic pillars for sustainable agricultural development (Bhattarai and Pandit, 2023). Literacy enhances agricultural productivity in Nepal by enabling farmers to adopt modern technologies, interpret extension advice, and optimize resource allocation in smallholder systems (Pudasaini, 1983a; 1983b). Nakano et al. (2018) documented that farmer training increases the adoption of technologies and increases productivity and profitability in farming. Higher household income and access to credit enable the purchase of quality seeds, fertilizers, and other inputs, which increase yields and returns (Boansi et al., 2024).

Adhikari et al. (2024) also found that pest and disease infestations, followed by inadequate irrigation were the main challenges in bean production in Tilagufa municipality of Kalikot. The incidence of insect pests, such as aphids, whiteflies, jassids, leaf miners, and pod borers, was initiated 25 days after sowing until harvesting (Kumar et al., 2023). Agricultural productivity is reduced by anthracnose in beans by 61.5% (Dhungana et al., 2025). Plant diseases are among the major constraints to achieving potential crop yields, and the costs associated with disease damage and management can substantially influence the overall economics of crop production (Oerke, 2006). Agronomic attributes were enhanced, and anthracnose infection was reduced under cultivar mixtures of beans compared to their sole cropping, both for trailing- and bushy-type beans (Prasad et al., 2016). Improving the efficiency of vegetable marketing in Nepal requires strengthening market information systems that provide timely demand and supply information to producers, traders, and consumers, which helps in making better production and marketing decisions and supporting the country’s goal of becoming self-reliant in vegetable production (Malla, 2021).

5 Conclusion

French bean cultivation in Kalikot district is a profitable and important source of food and income, which is reflected by a B:C ratio greater than 1.0, indicating good potential for expansion and commercialization. However, production is constrained mainly by inadequate irrigation, high disease and pest incidence, particularly anthracnose disease and pests such as aphids and pod borer, limited access to quality inputs, and reliance on traditional practices. Marketing problems, such as unorganized markets and dependence on intermediaries, further reduce farmers returns. The MLR results indicated that cultivated area, irrigation, annual household income, and training significantly influenced production. Productivity is greater for farmers with training, cooperative membership, and literacy. French bean production is promising in the Kalikot district of Nepal, but sustainable growth requires integrated improvements in irrigation, technical training, input supply, pest and disease management, and market organization to enhance productivity and farmer income.

Authors' contributions

S Panta conceived and designed the study, led the fieldwork, performed the data analysis, and prepared the manuscript. S Pandey provided methodological support and assisted in interpreting the findings. P Dhungana contributed to literature review, data validation, and manuscript revision. L Pokhrel coordinated data collection and supported field activities. S Pant assisted with fieldwork and data entry. S Regmi supervised data collection and contributed to data analysis. All authors read and approved the final manuscript.

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Research Article Open Access

Effect of Seed Priming on Germination and Seedling Growth of Cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0007
Received: 05 Nov., 2025
Accepted: 26 Feb., 2026
Published: 30 Mar., 2026

Preferred citation for this article:
Yadav S., Chaulagai B., Shrestha P., and Lamsal G., 2026, Effect of seed priming on germination and seedling growth of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, International Journal of Horticulture, 16(2): 77-87 (doi: 10.5376/ijh.2026.16.0007)

Abstract Cucumber (*Cucumis sativus* L.) is high-value vegetable in Nepal, known for its high nutritive value, high water and fiber content. However, cucumber faces low and inconsistent germination rates and poor seedling growth. Seed priming is a viable option to address these issues. Hence, an experiment was conducted from March to July, 2024 in Syangja, Nepal to analyse the effect of seed priming on germination and seedling growth of cucumber under high-tech polyhouse condition. The experiment was laid out in Completely Randomized Design (CRD) with ten treatments i.e. T_1: Control, T_2: Hot water (45 °C for 5 minutes), T_3: GA_3 100 ppm, T_4: GA_3 200 ppm, T_5: KNO_3 1%, T_6: KNO_3 3%, T_7: Cow urine 5%, T_8: Cow urine 10%, T_9: Vermiwash 10%, and T_{10}: Vermiwash 20%, each replicated three times. The results revealed that significantly the highest germination percentage (88%), seed vigour index-I (2,643.83), seed vigour index-II (22,555.33), fresh root weight (0.51 g) and earliest days to 50% germination (6 days) were recorded from the seed primed with hot water (45 °C for 5 minutes). Significantly the earliest mean germination time (6.06 days), highest speed of germination (0.49) and highest dry shoot weight (240 mg) were recorded in KNO_3 1%, while dry root weight was maximum in GA_3 200 ppm (46.00 mg). Hot water significantly enhanced germination percentage and overall seed vigour; KNO_3 1% reduced MGT and improved germination speed; GA_3 200 ppm promoted root dry matter accumulation. In practical applications, the choice of priming method should be based on target trait, as well as cost and availability considerations.
Keywords Cucumber (*Cucumis sativus* L.); Germination; Hot water; Potassium nitrate; Seed priming

1 Introduction

Cucumber (*Cucumis sativus* L.) is one of the economically important cucurbits grown during summer season in hills and terai region of Nepal. Cucumber is low in calories and contains soluble fiber, high level of vitamins like C, K, other traces of minerals and antioxidants (Murad and Nyc, 2016). The nutritive value of 100 g of edible cucumber contains 12 calories of energy, 0.6 g of protein, 0.1 g of fat, 2.2-3.6 g of carbohydrates, 0.5 g of dietary fiber, 14 mg of Ca, 15 mg of Mg, 124 mg of K, 24 mg of P (Shakuntala et al., 2020).

Seed priming is a pre-sowing strategy for influencing seedling development by modulating pre-germination metabolic activity prior to the emergence of radicle and generally enhance rapid, uniform emergence and plant development to achieve higher yield (Black and Bewley, 2000). It is a technique to elevate the germination percentage and reduce the time of seedling emergence along with improvement in uniformity of germination and emergence in field condition (Dhal et al., 2022). Hydro-priming enhance the seed germination, growth and uniform seedling growth in the field in various crops (Adebisi et al., 2012), and increases the speed of germination, decreases mean germination time (MGT), increases seed vigour index (SVI) (Shakuntala et al., 2020). GA_3 play essential role in plant growth and development (Bai et al., 2016), chlorophyll biosynthesis, carbohydrate metabolism (Varier et al., 2010), and increases germination by 30.56% (Behera, 2016). KNO_3 improves seed parameters of cucumber and other vegetables (Ghassemi-Golezani and Esmaeilpour, 2008). Cow urine 10% shows positive influence in capsicum due to presence of physiologically active substances (Ambika and Balakrishnan, 2015). Vermiwash priming increases the first and final count germination compared to control (Sowmya et al., 2022). Fathima and Sekar (2014) revealed that vermiwash treatment was most effective in promoting seedling growth, including maximum hypocotyl and radicle length.

Poor germination and erratic seedling growth were major factors to obstruct the seedling emergence and lower production of cucumber respectively. Effective results of seed priming on germination and seedling growth may be useful in making cucumber growers aware about the benefits of seed priming. Hence, the experiment was conducted to assess the effect of seed priming on germination and seedling growth of cucumber.

2 Materials and Methods

2.1 Experimental site

The study was conducted in high-tech polyhouse at the demonstration site of Agriculture Knowledge Center (AKC) Office, Putalibazar, Syangja from March to July, 2024. Syangja district lies in mid-hill region at altitude 300-2,266 masl. It lies at latitude 28º4ˈ6ˈˈN and longitude 83º52ˈ0ˈˈE.

The morning temperature at 6:00 am remained relatively stable (20 °C–23 °C) (Figure 1). The afternoon temperature at 2:00 pm consistently recorded the highest values (35 °C–40 °C), while the evening temperature at 6:00 pm was moderate (30 °C–35 °C). This pattern indicates a clear diurnal fluctuation, with peak temperatures occurring in the afternoon and minimum values in the early morning.

Relative humidity was highest during the morning (80%–100%), lowest in the afternoon (25%–35%), and moderate in the evening (35%–50%) (Figure 2). An inverse relationship between temperature and relative humidity was evident, with higher daytime temperatures corresponding to lower humidity levels.

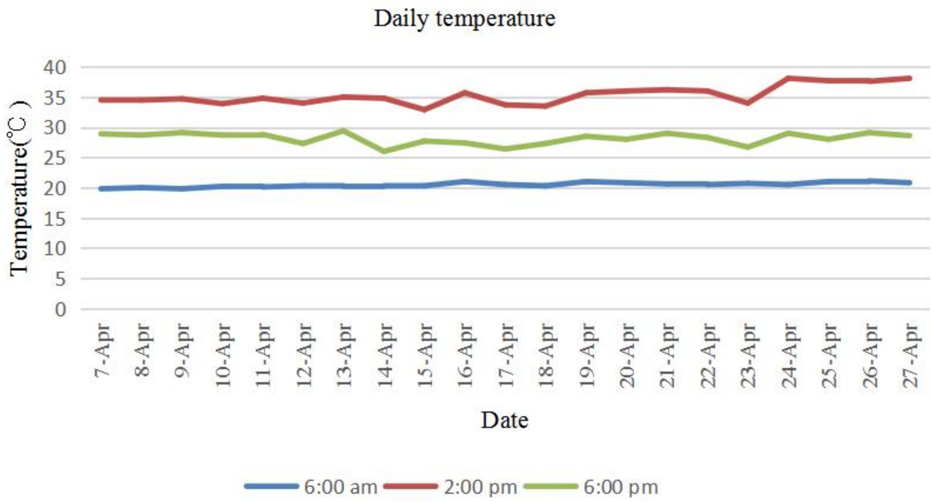

Figure 1 Daily temperature of the high-tech polyhouse during experimental period

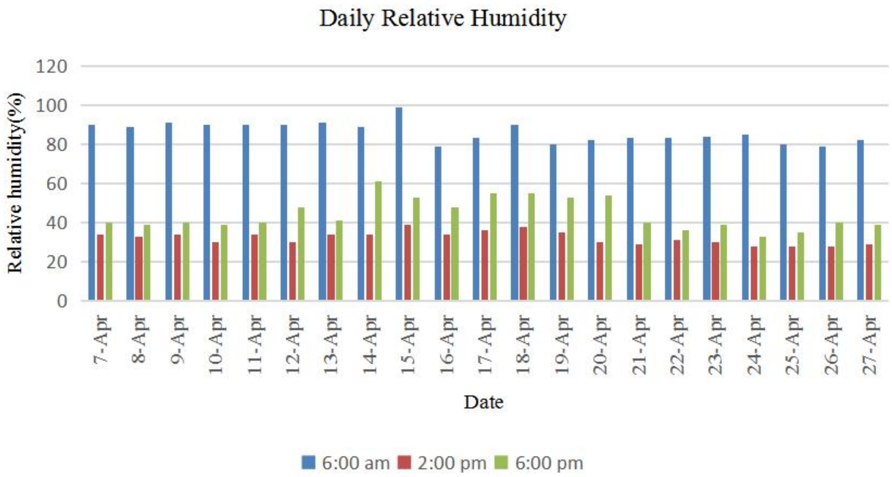

Figure 2 Daily relative humidity of the high-tech polyhouse during experimental period

2.2 Plant material and seed source

The seeds were purchased from Agrovet and produced by Muktinath Krishi Company. The packet included following labellings:

- Variety name: Bhaktapur Local
- Moisture content: 6%
- Thousand-seed weight: 32 g

2.3 Seed priming treatments

Ten different types of treatments and concentrations were evaluated for an experiment. Control, Hot water, Gibberellic acid (GA_3), Potassium nitrate (KNO_3), Cow urine and Vermiwash were used with selective concentration (Table 1).

Table 1 Details of the treatments evaluated in the experiment

Treatments	Details
T_1	Control (unsoaked)
T_2	Hot water (45 °C for 5 minutes)
T_3	GA_3 100 ppm
T_4	GA_3 200 ppm
T_5	KNO_3 1%
T_6	KNO_3 3%
T_7	Cow urine 5%
T_8	Cow urine 10%
T_9	Vermiwash 10%
T_{10}	Vermiwash 20%

Note: GA_3- gibberellic acid; KNO_3- potassium nitrate; ppm- parts per million

2.4 Procedure of seed priming

Seeds were primed for 24 hours in priming solution of KNO_3, GA_3, Cow urine and Vermiwash. Similarly, hot water (45 °C) priming of seed was done for 5 minutes. Seeds were soaked in 100 mL priming solutions of the respective treatment solutions. Then the seeds were re-dried to near original moisture level at room temperature for 24 hrs. For control, seeds were not treated and it were used as in the original condition.

For priming with GA_3, 1 g of GA_3 was taken in a test tube and 3 mL of 70% ethyl alcohol was added and it was shaked with low heat. The heated solution of the test tube was diluted with distilled water to make 1,000 ppm of 1 litre stock solution of GA_3. Finally, it was diluted with distilled water to prepare 100 ppm and 200 ppm GA_3 solutions. For the preparation of KNO_3 1% solution, 1 g of KNO_3 was taken and diluted with distilled water to make 100 mL solution and 3 g of KNO_3 was taken and diluted with distilled water to make 100 mL solution of KNO_3 3%.

2.5 Experimental design and layout

The experiment was laid out in Completely Randomized Design (CRD) with ten treatments and three replications. “Each treatment consisted 50 seeds, with 3 replications, resulting in total sample size of 150 seeds per treatment.” For seedling measurements, the 10 sample plants were randomly selected from each tray, and then tray mean were calculated. Subsequently, ANOVA were performed using the tray as an experimental unit (n=3).

2.6 Germination assessment

Among 50 seeds sown in each tray, the number of seed got emerged were only taken for an assessment considering 50 as a whole. Observation was done on daily basis in the morning time and data were recorded according to the data observed. Calculation of germination parameters are given below:

Number of normal seedlings from each replication were counted and germination percentage was calculated by using formula given by Piri et al. (2009):

$$\text{Seed germination percentage} = \frac{\text{Number of normal seedlings}}{\text{Total number of seeds}} \times 100\%$$

Mean germination time (MGT) was the time taken for a lot to germinate. The lower the MGT the faster the population of seeds were germinated (Dhakal and Subedi, 2020):

$$\text{MGT}= \frac{\sum (D*n)}{\sum n}$$

Where, D =the number of days counted from the beginning of germination, n = number of seed germinated on each day.

Seedling Vigour Index (SVI) was calculated by using following formula (Dhakal and Subedi, 2020):

SVI-I = Germination percentage × Total seedling length (cm)
SVI-II = Germination percentage × seedling dry weight (mg)

Where, SVI-I indicates vigour of seed in relation with length of seedling while SVI-II indicates vigour of seed in relation with dry matter accumulates of seedling.

Days to 50% germination was the time taken to get 50% germination of final germination percentages (Coolber et al., 1990).

Speed of germination (BRI) was calculated by using following formula (Bartlett, 1937):

$$\text{BRI}= \frac{p1+(p1+p2)+(p1+p2+p3)+\ldots+(p1+p2+p3+\ldots+pn}{N(p1+p2+\ldots+pn)}$$

Where, $p1+p2+p3+\ldots$and pn are the germination (%) at 1st, 2nd, 3rd and nth day, respectively and 'N' is the total number of days taken for germination.

2.7 Seedling growth measurement

Seedling growth was evaluated by sampling plants at 21 days after sowing. The sampled seedlings were carefully uprooted to avoid damaging the roots. After collection, the roots were separated from the stem portions and different growth parameters were measured. For each treatment, ten representative seedlings were selected, and the mean values were calculated and recorded for further analysis.

Root length was measured after the seedlings were uprooted. The measurement was taken from the tip of the root apex to the base of the root system at 21 days after sowing, following the method described by Dhakal and Subedi (2020). Shoot length was determined by measuring the distance from the base of the growing medium to the tip of the shoot apex.

For fresh weight determination, sample plants from each experimental unit were collected and separated into root and shoot portions by cutting with a knife. The stem portion was weighed using a weighing machine to determine shoot fresh weight, and the values were recorded in grams. Similarly, the root portion was weighed separately to obtain root fresh weight, and the average values were calculated for each treatment.

To determine dry weight, the shoot portions were first weighed to obtain fresh weight and then placed in envelopes. These samples were dried in a hot air oven at 105 °C for 24 hours and then allowed to cool as described by Khatiwada and Adhikari (2020). After drying, the shoot samples were weighed and the shoot dry weight was recorded in milligrams. The same procedure was followed for the root portions: after measuring fresh weight, the root samples were packed in envelopes, dried in a hot air oven at 105 °C for 24 hours, cooled, and then weighed to obtain root dry weight in milligrams. The average values were calculated for analysis.

2.8 Statistical analysis

All the recorded data were arranged systematically treatment wise under three replications using Microsoft Excel version 16.89.1. To determine the significant result between the treatments, Analysis of variance (ANOVA) was carried out using R studio version 4.4.1 and DMRT was used for mean separation at 5% level of significance ($p<0.05$).

3 Results and Analysis

3.1 Germination percentage, mean germination time (MGT) and days to 50% germination (T_{50})

The results on germination percentage, mean germination time (MGT) and days to 50% germination (T_{50}) affected by different seed priming method are presented in Table 2. Germination percentage, mean germination time, and days to 50% germination were significantly affected by different seed priming techniques.

Table 2 Effect of seed priming on germination percentage, mean germination time (MGT) and days to 50 % germination (T_{50}) of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, 2024

Treatments	Germination parameters		
	Germination percentage	MGT (Days)	T_{50} (Days)
Control	73.34^{c}	6.90^{a}	6.83^{a}
Hot water (45 °C for 5 minutes)	88.00^{a}	6.30^{b}	6.00^{b}
GA_3 100 ppm	84.00^{ab}	6.22^{bc}	6.00^{b}
GA_3 200 ppm	81.34^{abc}	6.34^{bc}	6.00^{b}
KNO_3 1%	80.67^{abc}	6.06^{c}	6.00^{b}
KNO_3 3%	80.00^{abc}	6.19^{bc}	6.00^{b}
Cow urine 5%	77.34^{bc}	6.27^{bc}	6.00^{b}
Cow urine 10%	80.00^{abc}	6.26^{bc}	6.00^{b}
Vermiwash 10%	76.67^{bc}	6.17^{bc}	6.00^{b}
Vermiwash 20%	80.67^{abc}	6.41^{b}	6.00^{b}
CV (%)	5.52	1.98	0.75
$LSD_{0.05}$	7.54	0.21	0.07
Grand mean	80.20	6.31	6.08
SEm (±)	2.55	0.07	0.02
F-test	*	***	***

Note: Mean within the column followed by the same letter/s are not significantly different at 5% level of significance by DMRT. * Significant at 5% ($p<0.05$), ** Significant at 1% ($p<0.01$), *** Significant at 0.1% ($p<0.001$), NS= non-significant at 5% ($p>0.05$), SEm= Standard Error of mean, LSD= Least significant difference, CV= Coefficient of variance, MGT= Mean germination time and T_{50}= Days to 50% germination

Significantly the highest germination percentage (88.00%) was found in hot water (45 °C for 5 minutes). GA_3 100 ppm (84.00%), GA_3 200 ppm (81.34%), KNO_3 1% (80.67%), Vermiwash 20% (80.67%), KNO_3 3% (80.67%) and Cow urine 10% (80.00%), also showed increased germination percentage but were non-significant among themselves (LSD=7.54), while the lowest germination percentage (73.34%) was observed in control.

Significantly the highest mean germination time was recorded in control (6.90 days), while the lowest MGT was found in KNO_3 1% (6.06 days), which was not significantly different from Vermiwash 10% (6.17 days), KNO_3 3% (6.19 days), $GA_3$100 ppm (6.22 days), Cow urine 10% (6.26 days), Cow urine 5% (6.27 days) and GA_3 200 ppm (6.34 days). Significantly the highest T_{50} (6.83 days) was found in control and the lowest T_{50} was found in hot water (6.00 days) which was not significantly different from Vermiwash 10% and 20%, Cow urine 5% and 10%, KNO_3 1% and 3%, GA_3 100 ppm and 200 ppm.

3.2 Seed vigour index (SVI-I and SVI-II) and speed of germination (BRI)

The results on Seed vigour index I (SVI-I), Seed vigour index II (SVI-II) and speed of germination (BRI) are presented in Table 3. Significantly the highest SVI-I (2,643.83) was found in hot water (45 °C for 5 minutes) which was not significantly different from KNO_3 1% (2,506.23) and GA_3 200 ppm (2,502.24), while the lowest SVI-I (1,828.13) was found in control.

Table 3 Effect of seed priming on seed vigour index and speed of germination of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, 2024

Treatments	Seed vigour index (SVI)		Speed of germination
	SVI-I	SVI-II	BRI
Control	1,828.13^{d}	16,823.33^{d}	0.40^{d}
Hot water (45 °C for 5 minutes)	2,643.83^{a}	22,555.33^{a}	0.46^{bc}
GA_3 100 ppm	2,202.97^{bcd}	21,026.00^{ab}	0.47^{abc}
GA_3 200 ppm	2,502.24^{ab}	21,933.33^{ab}	0.46^{bc}
KNO_3 1%	2,306.23^{abc}	22,006.67^{ab}	0.49^{a}
KNO_3 3%	2,031.86^{cd}	17,776.00^{cd}	0.48^{abc}
Cow urine 5%	2,044.51^{cd}	19,702.67^{bc}	0.47^{abc}
Cow urine 10%	2,167.02^{bcd}	20,877.33^{ab}	0.47^{abc}
Vermiwash 10%	1,966.06^{cd}	17,946.00^{cd}	0.48^{ab}
Vermiwash 20%	2,106.60^{cd}	19,580.67^{bc}	0.45^{c}
CV (%)	9.40	6.41	0.46
$LSD_{0.05}$	349.07	2,188.86	0.02
Grand mean	2,179.94	20,022.73	0.46
SEm (±)	118.30	741.98	0.00
F-test	**	***	***

Note: Mean within the column followed by the same letter/s are not significantly different at 5% level of significance by DMRT. * Significant at 5% (p<0.05), ** Significant at 1% (p<0.01), *** Significant at 0.1% (p<0.001), NS= non-significant at 5% (p>0.05), SEm= Standard Error of mean, LSD= Least significant difference, CV= Coefficient of variance, SVI-I= Seed vigour index-I, SVI-II= Seed vigour index-II and BRI= Speed of germination

Significantly the highest SVI-II (22,555.33) was found in hot water which was not significantly different from KNO_3 1% (22006.67), GA_3 200 ppm (21,933.33), GA_3 100 ppm (21,026.00) and Cow urine 10% (20,877.33), while the lowest SVI-II (16,823.33) was found in control. This finding was also supported by Sowmya et al. (2013), where KNO_3 1% had highest SVI-II.

Significantly the highest BRI (0.49) was found in KNO_3 1% which was not significantly different from KNO_3 3% and Vermiwash 10% (0.48), Cow urine 5% and 10% (0.47), GA_3 100 ppm (0.47), while the lowest BRI (0.40) was found in control.

3.3 Shoot length and root length (cm)

The results on shoot length and root length are presented in Table 4. The effect of different seed priming treatments on shoot length did not show significant differences. Similar finding was reported by Al Sahil (2016).

Root length was highly significant for different seed priming techniques. Significantly, the highest root length was found in GA_3 200 ppm (21.15 cm) which did not differ significantly from the hot water (20.09 cm) treatment, while the lowest root length was found in control (15.49 cm). Vermiwash 10% (15.75 cm), Cow urine 5% (16.56 cm), Vermiwash 20% (16.62 cm), KNO_3 3% (16.67 cm), GA_3 100 ppm (17.08 cm), Cow urine 10% (17.26 cm) and KNO_3 1% (17.76 cm) also showed lower root length but were non-significant among themselves.

3.4 Fresh shoot weight and fresh root weight (g)

The results on fresh shoot and fresh root weight are presented in Table 5. The effect of different seed priming treatments on fresh shoot weight did not show significant differences. According to Farooq et al. (2007), Osmo-priming or chemo-priming did not improve the seedling fresh weight in melon. Seed pre-soaking treatments were recorded non-significant for seedling fresh weight in cucumber (Al Sahil, 2016).

Table 4 Effect of seed priming on shoot length and root length of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, 2024

Treatments	Shoot length (cm)	Root length (cm)
Control	9.42	15.49^{c}
Hot water (45 °C for 5 minutes)	9.91	20.09^{ab}
GA_3 100 ppm	9.14	17.08^{bc}
GA_3 200 ppm	9.56	21.15^{a}
KNO_3 1%	10.81	17.76^{bc}
KNO_3 3%	8.79	16.67^{c}
Cow urine 5%	9.89	16.56^{c}
Cow urine 10%	9.75	17.26^{bc}
Vermiwash 10%	9.85	15.75^{c}
Vermiwash 20%	9.53	16.62^{c}
CV (%)	6.36	9.57
$LSD_{0.05}$	1.04	2.84
Grand mean	9.66	17.44
SEm (±)	0.35	0.96
F-test	NS	**

Note: Mean within the column followed by the same letter/s are not significantly different at 5% level of significance by DMRT. * Significant at 5% (p<0.05), ** Significant at 1% (p<0.01), *** Significant at 0.1% (p<0.001), NS= non-significant at 5% (p>0.05), SEm= Standard Error of mean, LSD= Least significant difference, CV= Coefficient of variance

Table 5 Effect of seed priming on fresh shoot and fresh root weight per seedling of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, 2024

Treatments	Fresh shoot weight (g)	Fresh root weight (g)
Control	2.79	0.35^{b}
Hot water (45 °C for 5 minutes)	2.84	0.51^{a}
GA_3 100 ppm	2.79	0.30^{bc}
GA_3 200 ppm	2.76	0.35^{b}
KNO_3 1%	3.11	0.30^{bc}
KNO_3 3%	2.58	0.37^{b}
Cow urine 5%	3.09	0.50^{a}
Cow urine 10%	3.01	0.45^{a}
Vermiwash 10%	2.52	0.25^{cd}
Vermiwash 20%	2.62	0.21^{d}
CV (%)	10.95	11.06
$LSD_{0.05}$	0.52	0.06
Grand mean	2.81	0.36
SEm (±)	0.17	0.02
F-test	NS	***

Note: Mean within the column followed by the same letter/s are not significantly different at 5% level of significance by DMRT. * Significant at 5% (p<0.05), ** Significant at 1% (p<0.01), *** Significant at 0.1% (p<0.001), NS= non-significant at 5% (p>0.05), SEm= Standard Error of mean, LSD= Least significant difference, CV= Coefficient of variance

Fresh root weight was very highly significant for different priming techniques. Significantly, the highest fresh root weight (0.51 g) was found in hot water which was not significantly different from Cow urine 5% (0.50 g) and Cow urine 10% (0.45 g), while the lowest fresh root weight was found in Vermiwash 20% (0.21 g). Similar finding was reported by Tania et al. (2019). Rehydration causes early emergence by influencing pre-germinative process for germination (Tania et al., 2019).

3.5 Dry shoot weight and dry root weight (mg)

The results on dry shoot weight and dry root weight are presented in Table 6. Dry shoot weight and root weight were very highly significant for different priming treatments. Significantly, the highest dry shoot weight was found in KNO_3 1% (240.00 mg), while the lowest dry shoot weight was found in KNO_3 3% (194.67 mg) which was not significantly different from control (197.34 mg), Vermiwash 10% (204.00 mg) and Vermiwash 20% (209.67 mg).

Significantly the highest dry root weight (46.00 mg) was found in GA_3 200 ppm, while the lowest dry root weight was found in KNO_3 3% (27.34 mg) which was not significantly different from GA_3 100 ppm (30.00 mg), Vermiwash 10% (31.34 mg), control (32.00 mg) Vermiwash 20% (32.67 mg) and KNO_3 1% (32.67 mg).

Table 6 Effect of seed priming on dry shoot weight and dry root weight per seedling of cucumber (*Cucumis sativus* cv. Bhaktapur Local) in Syangja, Nepal, 2024

Treatments	Dry shoot weight (mg)	Dry root weight (mg)
Control	197.34^{d}	32.00^{cd}
Hot water (45 °C for 5 minutes)	218.34^{bc}	38.00^{b}
GA_3 100 ppm	220.34^{bc}	30.00^{d}
GA_3 200 ppm	223.67^{b}	46.00^{a}
KNO_3 1%	240.00^{a}	32.67^{cd}
KNO_3 3%	194.67^{d}	27.34^{d}
Cow urine 5%	218.67^{bc}	36.00^{bc}
Cow urine 10%	222.00^{bc}	39.34^{b}
Vermiwash 10%	204.00^{cd}	31.34^{cd}
Vermiwash 20%	209.67^{d}	32.67^{cd}
CV (%)	4.4	8.37
$LSD_{0.05}$	16.20	4.92
Grand mean	214.86	34.53
SEm (±)	5.49	1.67
F-test	***	***

Note: Mean within the column followed by the same letter/s are not significantly different at 5% level of significance by DMRT. * Significant at 5% (p<0.05), ** Significant at 1% (p<0.01), *** Significant at 0.1% (p<0.001), NS= non-significant at 5% (p>0.05), SEm= Standard Error of mean, LSD= Least significant difference, CV= Coefficient of variance

4 Discussion

Germination behavior and seedling growth of cucumber were significantly influenced by seed priming. Among the treatments, hot water (45 ° C) priming showed superior performance in germination percentage and seed vigour indices, while KNO_3 1% outperformed in speed of germination. GA_3 200 ppm showed comparatively better dry matter accumulation. In contrast, control showed inferior performance across all parameters.

Hot water treatment enhances imbibition and stimulates several germination related-process, including the synthesis of GA_3, RNA, protein synthesis and DNA replication. This in turn may have weakened the endosperm, thereby promoting increased germination rate (Black and Bewley, 2000). KNO_3 Priming improved emergence and its time significantly in both carrot seed and *Clonostachys rosea* cv. IK726 (Bennett et al., 2009). Similar results were reported by Tania et al. (2019) in bitter gourd. Faster germination in seed priming with KNO_3 1%, than non-priming is likely due to its stimulation of metabolic processes during imbibition, which prepare seed for root emergence (Sowmya et al., 2013). This reduces mean germination time (Sowmya et al., 2022) and days to 50% germination. Similar finding was reported by Shim et al. (2009), where seed priming improves days to 50% germination than non- primed seed. According to Singh et al. (2019), seed soaked at (50-52) °C exhibited the highest seedling vigour index-I indicating that this temperature range significantly enhance seedling vigour. KNO_3 1% also recorded to show similar result (Sowmya et al., 2013). GA_3 200 ppm recorded higher SVI-I which was in accordance with Badu et al. (2022).

GA_3 200 ppm priming showed significant effect on root length and root dry matter accumulation of cucumber promoting root development through active stimulation of enzyme synthesis (hydrolytic enzyme) and enhanced cell elongation in the radicle region leading to highest root length. The results were observed for root length as earlier found by Badu et al. (2022). GA_3 priming showed improved assimilate partitioning toward root tissues and increased root sink strength for carbohydrate and other structural compounds leading to dry matter accumulation. Singh (1984), reported that GA_3 significantly increased dry root weight in seedling. KNO_3 1% showed best result in shoot dry matter accumulation because KNO_3 supports in supply of readily available nitrogen promoting protein synthesis and more efficient reserve mobilization and assimilation during early growth. Similar finding was reported by Farooq et al. (2007), where improvement in seedling dry weight was observed from seed primed with KNO_3 1% solution.

Distinct advantages can be revealed from comprehensive comparison among treatments. Hot water priming results in higher and uniform germination, making it beneficial for nursery establishment. For rapid and synchronized emergence of seedling, KNO_3 1% could be beneficial, while GA_3 200 ppm showed higher root dry matter biomass leads to potential improvement in transplant establishment. These trade-offs highlight the importance of selecting proper seed priming methods based on production objectives.

Beside of positive outcomes, the experiment was limited to single location and inside polyhouse condition. Absence of field validation restrict broader generalization. More studies are required under large and open field condition for better conformity.

5 Conclusion

Priming cucumber seed with hot water (45 °C for 5 minutes) proved to be effective for highest germination percentage. However, it was not significantly different from GA_3 100 ppm, and GA_3 200 ppm. Similarly, hot water was found to decrease days to 50% germination, increase seed vigour index-I, seed vigour index-II and have better effect on root length and fresh root weight. Mean germination time was decreased and the highest speed of germination was found in KNO_3 1%. Dry shoot weight was significantly affected by KNO_3 1% while GA_3 200 ppm showed significant effect on dry root weight. Control treatment consistently produced the lowest result in most of the parameters. Hence, in practical applications, the choice of priming method should be based on target trait, as well as cost and availability considerations to enhance most of the germination and seedling growth parameters of cucumber.

Authors' contributions

Saroj Yadav is the principal researcher who conceptualized the idea, collected and analysed the data, and prepared the manuscript. Bibas Chaulagai and Promise Shrestha helped Saroj Yadav in data collection, analysis, editing and proofreading of manuscript. Ganesh Lamsal helped in conceptualizing the idea, data analysis and proofreading of the manuscript. All authors read and approved the final manuscript.

Acknowledgements

We would like to extend our gratitude to the Agriculture and Forestry University (AFU), Rampur, Chitwan, Nepal, for providing a favorable environment for this study. Also, we are deeply thankful to our advisor, Assistant Professor Ganesh Lamsal (Department of Horticulture) for his invaluable guidance and support throughout the entire research work.

Competing interests

The authors declare that they have no competing interests.

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International Journal of Horticulture, 2026, Vol.16, No.2, 88-97
http://hortherbpublisher.com/index.php/ijh

Research Insights Open Access

Application of Plant Growth Regulators in Enhancing Loquat Fruit Set

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0008
Received: 10 Jan., 2026
Accepted: 28 Feb., 2026
Published: 05 Apr., 2026

Preferred citation for this article:
Wang X.C., and Li Z., 2026, Application of plant growth regulators in enhancing loquat fruit set, International Journal of Horticulture, 16(2): 88-97 (doi: 10.5376/ijh.2026.16.0008)

Abstract Loquat (*Eriobotrya japonica*), a key specialty fruit tree in southern China, enjoys high economic value due to its nutritious properties and unique flavor. However, in actual production, loquat often faces challenges with low fruit set and unstable yield, hindering the development of the industry. This study describes the physiological basis and key influencing factors of loquat fruit set, as well as the types and functional characteristics of commonly used plant growth regulators. The study focuses on their mechanisms of promoting fruit set through regulation of ovule development, pollen tube growth, and carbon and nitrogen metabolism. Furthermore, the study systematically reviews recent progress in the application of regulators in loquat cultivation, exploring the effects of different treatment methods, application timing, varietal responses, and comprehensive regulatory measures. Although regulators show promise in improving fruit set, they still face numerous challenges, including dosage safety, varietal adaptability, and the elucidation of regulatory mechanisms. This study holds the promise of achieving a synergistic improvement in loquat fruit set, yield, and quality, providing theoretical support and technical guidance for efficient cultivation and sustainable industrial development.
Keywords Loquat; Fruit-setting rate; Plant growth regulators; Hormonal regulation; Fruit tree cultivation

1 Introduction

Loquat (*Eriobotrya japonica* Lindl.), a subtropical evergreen fruit tree native to south-eastern China, is economically and nutritionally important. Loquat is widely cultivated in East Asia, the Mediterranean region, and South America and is prized for its good flavor, quick ripening, and high levels of vitamins, minerals, and antioxidant compounds (Su et al., 2024). Loquat is a key southern provincial fruit crop in China's Fujian, Zhejiang, and Sichuan provinces, and an important contributor to regional agricultural economies. Loquat production, however, is still constrained by agronomic problems and year-to-year yield variability relative to other dominant fruit crops.

One of the greatest limitations to loquat production is that it bears a very low percentage of fruit set, normally ranging from 1% to 5% when it is under natural pollination (Bons et al., 2019). The inefficiency of fruiting is mostly because of physiological fruit drop, partial pollination, and ovule abortion—limitation that is aggravated by unfavorable weather and suboptimal orchard management. Consequently, fruit production and quality are negatively affected, limiting the economic yield of loquat production and making the crop less competitive in the global fruit market.

Plant growth regulators (PGRs) also emerge as potential candidates to solve the problem of loquat fruit set in recent years. PGRs are naturally occurring or synthetic chemicals that have the capability to control endogenous hormone levels and physiological processes and to initiate reproductive development. Various PGR groups including auxins, gibberellins (GAs), cytokinins, ethylene inhibitors, and abscisic acid analogs have been studied for their capacity to induce pollen germination, ovule development, nutrient transport, and prevention of physiological drop of the fruit (Huang et al., 2021; Peng et al., 2022). PGR treatment was observed to have measurable effects on improving the retention and production of loquat fruit under open-field and protected cultivation regimes (Liang and Huang, 2024).

This study explored the research progress on plant growth regulators (PGRs) in promoting loquat fruit set, including the physiological basis of fruit set, the types and functional characteristics of commonly used PGRs, their mechanisms of action, and field application techniques. The study focused on practical challenges such as dosage optimization, varietal response differences, and potential side effects. The study aims to integrate the latest research findings to provide theoretical basis and practical guidance for increasing loquat yield and achieving sustainable production.

2 Physiological Basis and Influencing Factors of Loquat Fruit Set

2.1 Characteristics of flowering and fruit setting in loquat

Loquat (*Eriobotrya japonica*) is an evergreen tree that flowers commonly from autumn to winter with fruit formation in late spring to early summer. Loquat fruit growth is sigmoid and has a high correlation between the length of rapid growth and final fruit size. Both seed number and fruit size have a positive correlation and seed weight with flesh and fruit weight. During the stage of rapid growth, significant physico-chemical changes occur, including color alteration, development of sugar, and loss of firmness in fruit and organic acids, which are associated with high ethylene production and with a small peak of respiration. These findings indicate that fruit ripening of loquat on the tree is a climacteric process with comparatively minor levels of ethylene production in an initial stage of development (Amorós et al., 2003; Su et al., 2024).

2.2 Major physiological and environmental factors affecting fruit set rate

Loquat fruit set is controlled by a combination of environmental and physiological factors. Growth of the fruit is regulated by hormones to a great extent, particularly by auxin and gibberellin, and by auxin particularly during the stage of fruit enlargement. Recent multi-omics analysis pinpointed candidate genes such as ETHYLENE INSENSITIVE 4 (*EjEIN4*) and TORNADO 1 (*EjTRN1*) as key regulators of fruit weight and thus implying gene regulation of set and size of the fruit (Peng et al., 2022). Mineral nutrition is required as well since biennial concentrations in leaves and soil of iron, calcium, magnesium, zinc, potassium, and nitrogen significantly affect fruit set, soluble solid content, and acidity and thus both fruit set and quality (Huang et al., 2021). Sunburn and reduced fruit set and quality may be caused by environmental stresses such as high light intensity and temperature. Heat stress induces stress response and hormone signaling pathways levels of hormones and gene expression, and this is crucial through the participation of heat shock proteins and auxin in the heat stress response (Chen et al., 2021). Agronomic practices including fruit and flower thinning have been found to improve fruit set and fruit quality, with optimal thinning intensities yielding heavier and sweeter fruits and greater yield (Mostert et al., 2024; Nordi et al., 2025) (Figure 1).

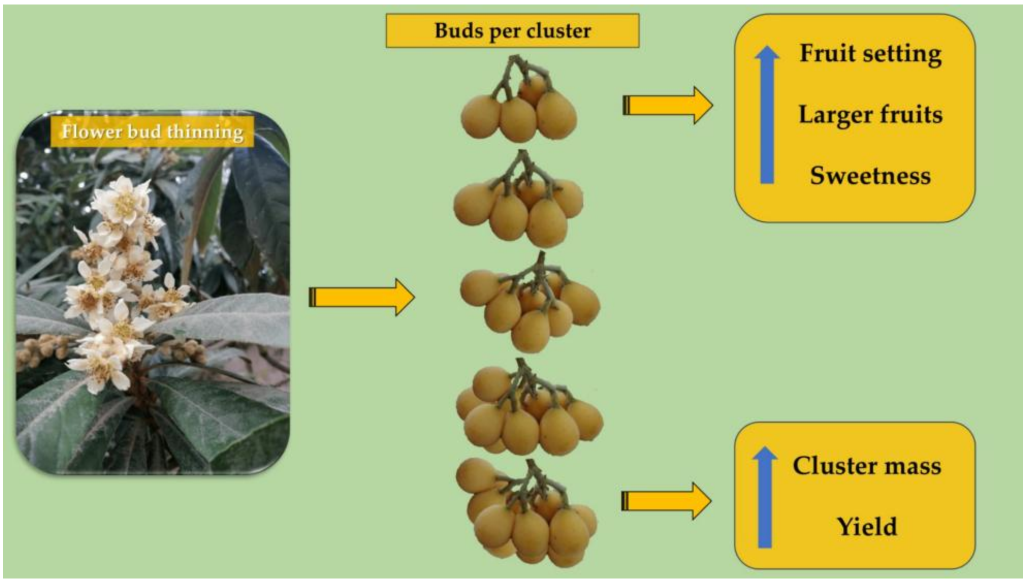

Figure 1 Relationship between fruit thinning intensity and fruit size and yield (Adopted from Nordi et al., 2025)

2.3 Types and mechanisms of flower and fruit drop in loquat

Flower and fruit abscission in loquat are caused by physiological and environmental factors. Physiological drop is more associated with abnormal cell division during the early stages of development and hormonal imbalances, particularly with auxin, gibberellin, and ethylene. Environmental aspects are also responsible, with genes like EjBZR1 playing a negative role in cell expansion and fruit growth and thus influencing the fruit drop tendency (Su et al., 2021). Environmental stresses like high temperature and nutritional deficiency also induce flower and fruit drop via the disruption of hormonal regulation and cell activities (Huang et al., 2021). Understanding of these mechanisms will further be helpful in devising methods for enhancing fruit set and yield in loquat.

3 Common Types and Functional Characteristics of Plant Growth Regulators

3.1 Auxins

Auxins are regulators of plant growth involved in the regulation of cell elongation, root formation, and organogenesis. Auxins are the central hormones in coordinating the plant response to external stimuli, and they constantly interact with other hormones in the regulation of synthesis, transport, and signal transduction. Auxins also play a role in fruit set, development, and abscission and typically synergize or antagonize other hormones to regulate plant growth and stress (Mazzoni-Putman et al., 2021; Thapa et al., 2024).

3.2 Gibberellins

Gibberellins are mostly involved in triggering stem elongation, seed germination, and flowering. Gibberellins are responsible for vegetative to reproductive transition growth and participate in fruit development and ripening. Gibberellins interact with other hormones such as auxins and abscisic acid and control growth and developmental processes, and their use may enhance fruit set and quality (Waadt et al., 2022; Jain et al., 2023).

3.3 Cytokinins

Cytokinins are shoot growth and cell division promoters. Cytokinins are the primary regulators of organogenesis, and they also delay leaf senescence and control mobilization of nutrients. Cytokinins act in conjunction with auxins to control root and shoot growth and can potentially control abiotic stress responses by impacting hormonal crosstalk as well as gene expression (Thapa et al., 2024).

3.4 Ethylene regulators

Ethylene is a gaseous hormone which controls fruit ripening, senescence, and abscission. Ethylene regulators suppress or stimulate ethylene action and can impact processes such as flower opening, fruit ripening, and stress responses. Ethylene opposes the action of abscisic acid and co-operates with auxins and cytokinins in various physiological activities (Jain et al., 2023).

3.5 Abscisic acid and other novel growth regulators

Abscisic acid (ABA) is a key stress-response hormone that mediates stomatal closure, seed dormancy, and drought and salt tolerance (Li, 2024). ABA interacts in a complex manner with auxin, cytokinin, and ethylene to regulate growth in response to stress. Other recently discovered growth regulators, such as brassinosteroids, jasmonic acid, salicylic acid, and strigolactones, also play significant roles in plant growth and stress adaptation, which tend to include intricate signaling processes and communication with classical hormones (Sabagh et al., 2021; Zahid et al., 2023; Ochatt, 2024) (Figure 2).

4 Mechanisms of Plant Growth Regulators in Enhancing Loquat Fruit Set

4.1 Regulation of hormonal balance and ovule development

Plant growth regulators such as auxins, gibberellins, cytokinins, and abscisic acid play a central role in regulating endogenous hormone levels to facilitate ovule production and fruitful reproduction. Exogenously applied PGRs may control the hormone balance to initiate division and differentiation within the reproductive organs, which maintains ovule viability and fertilization. For example, paclobutrazol changes the gibberellin, abscisic acid, and cytokinin levels, which lead to improved fruit set and quality because of its influence on hormonal regulation and inducing carbohydrate storage in young fruits (Bons and Kaur, 2019).

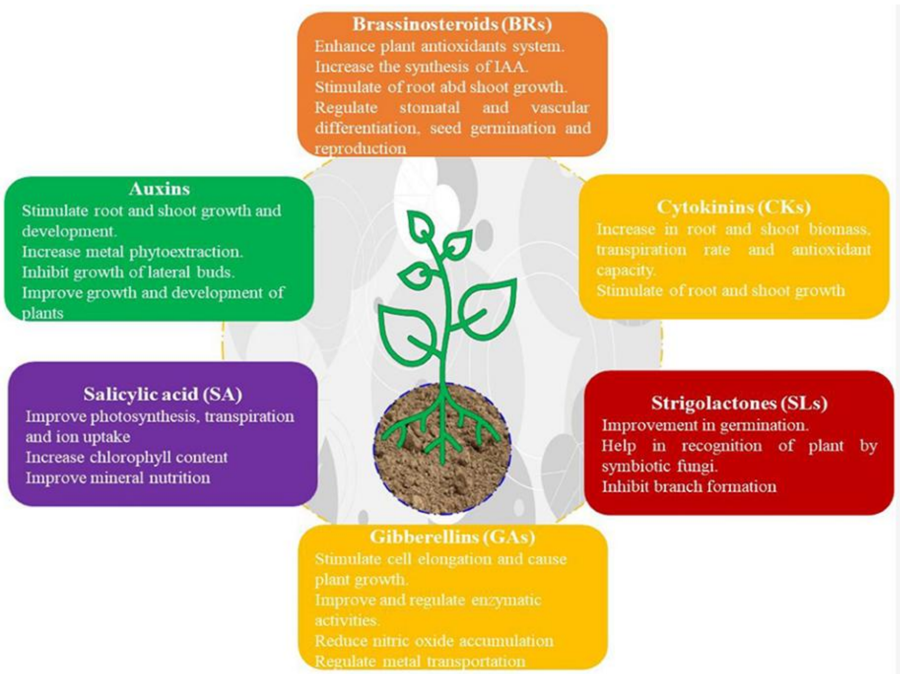

Figure 2 Role of selected PGRs on plant growth and development (Adopted from Sabagh et al., 2021)

4.2 Promotion of pollen germination and pollen tube growth

PGRs, particularly auxins and gibberellins, are said to induce pollen germination and pollen tube growth that is fundamental in successful fertilization and fruiting. With ideal hormonal conditions, these regulators facilitate the elongation of pollen tubes within the style, enhancing ovule fertilization possibilities and the development of fruit growth (Gill et al., 2023; Singh et al., 2024).

4.3 Inhibition of physiological fruit drop

Among the key benefits of PGR application is reducing physiological fruit drop. Auxins and gibberellins are predominantly used in an attempt to minimize pre-harvest fruit fall by maintaining the hormonal cues in the direction of fruit retention. The hormones reverse abscission signals, strengthening fruit attachment, and enhancing the rate of fruit retention, leading to enhanced yields (Suman et al., 2017). Ethylene regulators can be used to slow down abscission and enhance the life of fruit retention on the tree (Singh et al., 2024).

4.4 Influence on carbon-nitrogen metabolism and nutrient transport

PGRs control carbon-nitrogen metabolism and nutrient transport, which have significant roles in fruit development and quality. For instance, paclobutrazol enhances the accumulation of carbohydrates and stimulates the transport of nutrients to developing fruit, resulting in increased fruit size, weight, and quality. This is achieved through modifying the metabolic activities of the plant and increasing water and nutrient utilization efficiency, which favors extended fruit development under various environmental conditions (Desta and Amare, 2021; Zahid et al., 2023).

5 Application Strategies of Plant Growth Regulators for Improving Loquat Fruit Set

5.1 Spraying and smearing techniques

The effectiveness of plant growth regulators (PGRs) in enhancing loquat fruit set is highly dependent on the timing and concentration of application. Spraying is most effective when performed at critical developmental stages, such as the onset of flowering, early fruit set, and during the rapid fruit enlargement phase. For example, the application of synthetic auxins like 3,5,6-TPA at 15 mg/L during the early fruit growth stage or one month later significantly increased fruit size and accelerated ripening, with a 10% increase in fruit diameter compared to controls (Reig et al., 2016). Similarly, forchlorfenuron (a cytokinin-type PGR) applied at 20 mg/L at 24 and 38 days after bloom resulted in optimal improvements in fruit weight and quality (Zhang et al., 2025). The concentration must be carefully optimized, as excessive doses can lead to phytotoxicity or abnormal fruit development, while suboptimal concentrations may yield negligible effects (Desta and Amare, 2021; Kumar et al., 2023; Zhang et al., 2025).

Smearing techniques involve the direct application of PGRs to specific plant tissues, such as inflorescences or young fruits, to maximize local absorption and minimize wastage. For loquat, smearing is typically performed on the panicles or young fruitlets during pre-anthesis or immediately after fruit set. This targeted approach ensures that the PGRs are delivered precisely where hormonal regulation is most needed, promoting cell division and fruit retention. Technical guidelines recommend using a fine brush or cotton swab to apply the solution evenly, avoiding runoff and ensuring thorough coverage. Smearing is particularly useful for high-value cultivars or in research settings where precise dosing is required.

5.2 Mixing and combination of different regulators

The combined application of auxins and gibberellins has been shown to produce a synergistic effect on fruit set and development in loquat. Auxins (such as NAA or its synthetic analogs) promote cell division and fruit initiation, while gibberellins (such as GA_3) stimulate cell elongation and the formation of parthenocarpic fruits (Jiang et al., 2016; An et al., 2020; Jiang et al., 2020; He and Yamamuro, 2022). Studies have found that GA3 treatment significantly increases the fruit set rate of triploid loquats, with fruits in the treated group retained and developing after three weeks, whereas those in the control group largely abscised (Figure 3). Transcriptomic and proteomic analyses revealed that GA-induced fruit set is accompanied by the upregulation of auxin biosynthesis genes and cell division-related genes, reflecting the synergistic interaction between these hormones (Jiang et al., 2016; Jiang et al., 2020). Experiments have demonstrated that mixing NAA, CPPU (a cytokinin), and GA3 at specific concentrations (e.g., CPPU 40 mg/L + GA_3 50 mg/L + NAA 16 mg/L) can significantly improve fruit enlargement and quality, with the ratio and timing of regulator application being critical to maximizing the synergistic effect.

Cytokinins, such as forchlorfenuron (CPPU), are often combined with nutrient solutions to further enhance fruit set and quality. Cytokinins promote cell division and expansion, while nutrient supplementation ensures that developing fruits have adequate resources for growth (Aremu et al., 2020; Surya et al., 2021; Zhang et al., 2025). Forchlorfenuron application at 20 mg/L, for instance, not only increased fruit weight but also improved sugar-to-acid ratio and bioactive compound accumulation in loquat (Zhang et al., 2025). The integration of cytokinins with balanced nutrient sprays (including magnesium, zinc, and boron) has been shown to optimize fruit nutritional quality and reduce physiological disorders (Ali et al., 2021; 2024). Such combined strategies are particularly effective in orchards facing nutrient limitations or environmental stress.

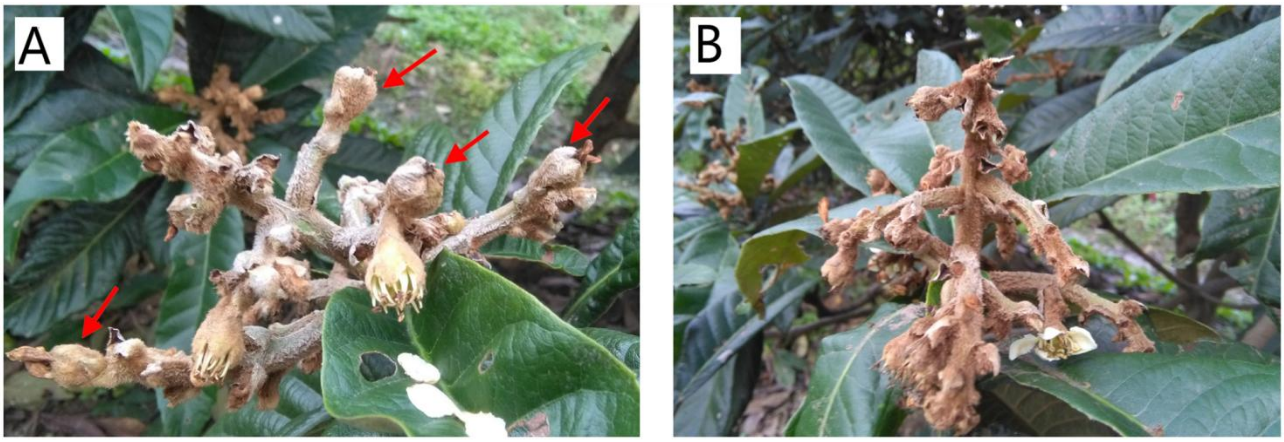

Figure 3 Development of the triploid loquat at 3 weeks after gibberellin (GA) treatment (Adopted from Jiang et al., 2016)
Image caption: A: GA treatment; B: Control (Adopted from Jiang et al., 2016)

5.3 Safety and standardized management

While PGRs offer substantial benefits, improper use can result in phytotoxicity, fruit deformities, or residue accumulation. Phytotoxic effects are often dose-dependent and can manifest as leaf burn, fruit drop, or abnormal growth patterns (Desta and Amare, 2021; Jain et al., 2023). To mitigate these risks, it is essential to adhere to recommended safety intervals between application and harvest, ensuring that residue levels remain within safe limits for human consumption (Kumar et al., 2023). Regular monitoring and residue analysis are advised, especially when using synthetic PGRs or in export-oriented production systems.

The adoption of standardized operational procedures is crucial for the safe and effective use of PGRs in loquat cultivation. Guidelines should specify the appropriate PGR type, concentration, timing, application method (spraying or smearing), and safety precautions (Desta and Amare, 2021; Jain et al., 2023; Kumar et al., 2023). Field training for workers, use of personal protective equipment, and record-keeping of application details are recommended best practices. Additionally, periodic field trials and extension services can help update growers on the latest research findings and regulatory requirements, promoting responsible and sustainable PGR use in loquat orchards.

6 Current Issues and Research Challenges

6.1 Dosage and safety concerns

PGR effect on loquat was found to be extremely dose-dependent in experiments, and the plant response vs. dosage relationship is not always linear. Under- and over-doses generate sub-optimal or toxic effects, which make it difficult to determine safe and optimal dosages for growth stages and organs. This diversity underscores the need for proper dosage standards to avoid unwanted impacts on plant health and fruit quality (Surya et al., 2020; Desta and Amare, 2021; Surya et al., 2021).

6.2 Regional adaptability differences due to variety and climate factors

Loquat varieties and PGR sensitivity vary significantly depending on genetic origin and environmental factors. Climatic conditions of the region, irrigation system, and stress severity (e.g., drought stress, frost stress) influence loquat plant response to PGR application. Regional differences in this context make it challenging to attempt overall application guidelines and highlight the need for ongoing location- and variety-dependent investigations (Gugliuzza et al., 2020; Wang et al., 2021).

6.3 Potential side effects on fruit development and quality

While PGRs can induce growth and stress tolerance, there is potential for unforeseen side effects on fruit form, nutritional content, and overall quality. For example, some treatments could increase some of the growth qualities but negatively affect others, e.g., leaf or fruit form, or not have a significant impact on all the desired qualities. The ignoring of potential negative effects on postharvest quality and fruit development remains a significant concern (Surya et al., 2020).

6.4 Lack of molecular-level understanding of regulatory mechanisms

In contrast, there is scant information on the molecular bases of the physiological and biochemical responses of PGRs in loquat (Tranbarger and Tadeo, 2025). Gene expression and signal transduction mechanisms have started to be explored in more recent investigations on PGR-induced stress responses, but overall knowledge at the molecular level is sporadic. This knowledge gap limits the possibility for optimization of PGR application and design of targeted interventions for improved fruit set and stress resistance (Sabagh et al., 2021; Wang et al., 2021).

7 Future Research Directions and Application Prospects

7.1 Screening and development of efficient and low-toxicity new growth regulators

Current research is laying a lot of emphasis on the synthesis of new PGRs with low toxicity and high activity. Synthetic researches are being attempted towards synthesizing new classes of PGRs such as phenylurea derivatives and phytohormone functional analogues with increased bioactivity and reduced toxicity. Encapsulation technology and micro/nano-formulations have also been explored to enhance stability, reduce the environmental impact, and enable controlled release, reducing toxicity and enhancing efficacy (Campos et al., 2023; Yan et al., 2023; Chen et al., 2024).

7.2 Integration with loquat genomics and hormone signaling pathways

Intersecting PGR treatment with genomic and transcriptomic research is a direction of the future. Current studies have made headways in deciphering the molecular mechanism of PGR activity in loquat, such as modification of hormone signaling pathway and stress response gene. For instance, transcriptome profiling characterized candidate genes and transcription factors of hormone signaling and stress response, which can be used as a basis for precision breeding and targeted application of PGR (Wang et al., 2021; Dongariyal et al., 2024).

7.3 Construction of precision regulation models and integration with digital agriculture

The future of PGR use is in precision agriculture where computer models and digital technologies can more accurately tailor timing, rate, and combinations of PGRs. Advances in metabolomics, genomics, and digital sensing technologies can bring predictive modeling of PGR response, which can facilitate site-specific and cultivar-specific management. The integration will optimize fruit set, yield, and quality and reduce resource utilization and environmental footprint (Gugliuzza et al., 2020; Zhang et al., 2025).

7.4 Comprehensive regulation strategies based on coordinated improvement of fruit set, yield, and quality

Systems approach is needed, incorporating PGRs with other agronomics (e.g., fertilization, irrigation) and employing molecular information to steer increases in fruit set, yield, and quality. Multi-component approaches, e.g., combining PGRs with fertilizers or biostimulants, have been documented to show synergistic action on loquat growth and stress tolerance. Multi-factorial experiments and systems-level optimization are to be accorded importance in the future for high-quality and sustainable production (Surya et al., 2020; Surya et al., 2021; Campos et al., 2023).

8 Concluding Remarks

Modern research shows that PGRs such as auxins, gibberellins, cytokinins, and chemicals such as paclobutrazol are very effective in controlling fruit set, yield, and quality of loquat and other fruit trees. The regulators promote internal physiological processes, suppress fruit drop, and reverse the detrimental effects of abiotic stresses such that fruit retention and yield are enhanced.

The application of PGRs has become an essential component of modern fruit production, offering a practical means to boost productivity and fruit quality. By optimizing hormonal balance, PGRs not only increase fruit number and weight but also improve nutritional and market value, making them invaluable for efficient and sustainable loquat cultivation.

The application of PGRs has become an essential component of fruit production today, offering a feasible measure to enhance productivity and fruit quality. PGRs not only increase fruit quantity and weight but also improve nutritional and market value by regulating hormonal balance, making them indispensable for productive and sustainable loquat cultivation.

Acknowledgments

The authors thank Ms. Wang for her support and assistance in data collection and material compilation. The authors also thank the two anonymous reviewers for their careful review of the 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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International Journal of Horticulture, 2026, Vol.16, No.2, 98-104
http://hortherbpublisher.com/index.php/ijh

Research Report Open Access

Effects of Different Mulching Materials on Growth and Yield of Okra (*Abelmoschus esculentus* L. Moench) cv. Arka Anamika in East Rukum, Nepal

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0009
Received: 27 Dec., 2025
Accepted: 26 Mar., 2026
Published: 20 Apr., 2026

Preferred citation for this article:
Magar P., Lama J., and Devkota R., 2026, Effects of different mulching materials on growth and yield of okra (*Abelmoschus esculentus* L. Moench) cv. Arka Anamika in East Rukum, Nepal, International Journal of Horticulture, 16(2): 98-104 (doi: 10.5376/ijh.2026.16.0009)

Abstract A field study was conducted from 10th April to 24th June 2024 to evaluate the effects of different mulching materials on the growth and yield of okra, specifically the Arka Anamika variety, and to compare yield performance across the various mulching treatments. The experiment was carried out at Dhakalbara, Sisne Rural Municipality-6, East Rukum, Nepal, using a Randomized Complete Block Design (RCBD). Six treatments were tested: T1 (black plastic mulch), T2 (control), T3 (mustard straw), T4 (banmara), T5 (sawdust), and T6 (leaf litter), each replicated four times. The results indicated that mulching type had a significant influence on both growth and yield parameters. The highest plant height was recorded from black plastic mulch at 25 days after sowing (DAS) (8.61 cm), 40 DAS (22.37 cm), and 60 DAS (74.87 cm), compared to other treatments. Black plastic mulch consistently produced the tallest plants, followed by mustard straw mulch (20.17 cm and 68.82 cm), which showed moderately improved growth compared to the other treatments. In addition to plant height, black plastic mulch also promoted a higher number of leaves per plant and resulted in superior yield performance. Black plastic mulch produced the highest average fruit weight (245.80 g), which was statistically superior to most organic mulches and comparable to the control plot (193.70 g). The highest productivity (14.897 Mt/ha) was recorded from black plastic mulch, followed by control (11.739 Mt/ha). The findings confirm that mulching, especially black plastic mulch, significantly enhances okra growth and productivity.

Keywords Okra (*Abelmoschus esculentus* L. Moench); Arka Anamika; Yield; Black plastic mulch; Mulching

1 Introduction

Okra production in mid-hill regions such as East Rukum is often constrained by uneven topography, limited irrigation facilities, and moisture stress during dry periods. Farmers in this region largely depend on rainfall, and soil moisture conservation remains a major challenge affecting crop growth and yield stability (Adhikari, 2018). Under such conditions, vegetable production, including okra, is highly affected due to moisture stress and limited soil management options. In addition, the availability and use of mulching materials are not well optimized under local farming conditions (Atreya et al., 2008).

Okra, scientifically known as *Abelmoschus esculentus*, is a renowned species belonging to the family Malvaceae. It holds great economic value as a vegetable crop, primarily cultivated in tropical and subtropical regions across the globe. It serves not only as a valuable source of fiber and nutrients but also plays a significant role in promoting human health. In Nepal, the total production of okra is 13.7 Mt/ha (MoALD, 2024). It is widely cultivated in Jhapa, Morang, Saptari, Bara, Chitwan, Rautahat, Kailali, and Dhanusa (Jha et al., 2018).

Mulching is the agronomic practice of leaving mulch on the surface of the soil for soil and water conservation and to favor plants' growth. Mulch refers to any material, other than soil or living vegetation, that performs the function of permanent or semi-permanent protective cover over the soil surface (Prosdocimi et al., 2016). When mulch is used, the soil becomes less compact and cooler, and its porosity and moisture improve. It also helps increase soil pH, organic matter, and the levels of nutrients like nitrogen, phosphorus, potassium, calcium, and magnesium in both the soil and the plant leaves (Adekiya et al., 2017). Mulching helps reduce weed growth, limits water loss through evaporation, and protects the soil from runoff and erosion, which together slow down soil degradation. As a result, it improves soil moisture retention, moderates soil temperature, enhances the soil's physical, chemical, and biological properties, and ultimately supports healthier crop growth and higher yields (Chauhan et al., 2024). Generally, straw, rice husk, crop residues or plastic mulch can be used as artificial mulch in crops (Wilhoit et al., 2019). An effective mulch should be affordable, readily available, simple to apply, and durable enough to resist being washed or blown away (Norman et al., 2011). However, limited studies have been conducted on the effectiveness of different mulching materials under the specific agro-ecological conditions of East Rukum, where environmental constraints differ significantly from the lowland areas of Nepal.

Therefore, the objective of this study was to evaluate the effect of different mulching practices on the growth and yield of okra, and to compare the yield performance under each mulching treatment. The study aimed to identify the most effective mulching method for improving okra yield and to generate useful information that can help farmers select suitable mulching practices for better crop productivity.

2 Materials and Methods

2.1 Experimental site

The experiment was conducted from 10th April to 24th June, 2024, at Dhakalbara, Sisne Rural Municipality-6, East Rukum District. The geographical location of the site is situated at an elevation of 1,568 m above sea level; the latitude is 28.612,803,06 ºNorth, and the longitude is 82.620,663,89 ºEast. The soil was classified as sandy loam soil with a medium level of nitrogen and has an alkaline pH (Kafle et al., 2025).

2.2 Experimental details

The experiment was conducted using a randomized complete block design with 6 treatments, and each treatment was replicated 4 times. The Arka Anamika variety was selected for experimental purposes. The variety was brought from the local agrovet. Six treatments, i.e., T1-black plastic mulch, T2-control, T3-mustard straw, T4-banmara (*Eupatorium adenophorum)*, T5-sawdust, and T6-leaf litter (*Acacia catechu*, *Syzygium cumini*, *Cedrus deodara)* were tested. The thickness of plastic mulch was 25 microns. 600 kilogram/ropani of decomposed farmyard manure were applied (Agriculture and Livestock Diary, 2081). Chemical fertilizers were not used as the site area consists of 100% organic farming practices.

2.3 Experimental unit

Each plot measured 2.1 m in length and 2.1 m in breadth. The R-R distance between crops was 30 cm, and the P-P distance was 30 cm. The individual plot area was 4.41 m^2 with 7 rows and 7 plants per row, giving a total of 49 plants in each plot. The distance between the blocks of replication was 50 cm, and within the treatments was 50 cm. The outer two rows and the outer two columns were designated as border plants, and data were recorded from the sample plants selected from the remaining inner area of the plot. Out of 7 rows, the outer 2 rows were taken as border plants, and the data were recorded from the sample plants selected within the remaining rows. The outer border was 50 cm from the plot.

2.4 Field preparation and layout

The field was ploughed using a mini tiller. Then the field was divided into 24 plots with each plot size of 2.1 m length and 2.1 m breadth in the appropriate layout of RCBD design. Measuring tape, pegs, and plastic ropes were used to carry out the layout of the field. Soil was treated with the recommended dose of *Metarhizium* biopesticides before sowing. Okra seeds were soaked in water for 24 hours and dried using a clean paper towel before sowing. 3 seeds per hill were sown in the field at a distance of 30 cm R-R distance and 30 cm P-P distance. Thinning of an extra 2 plants was done after satisfactory growth, leaving one behind. The okra seeds were sown on 20th April, 2024.

2.5 Data collection and measurements

Except border plants, 10 plants were chosen at random from the net plot and tagged to record observations on growth and yield metrics. Plant height and number of leaves per plant were recorded as vegetative parameters. Plant height (cm) was measured from the base of the plant to the tip of the apex or flower. The number of fully developed fresh leaves attached to the plants was counted and recorded.

Yield-related parameters included average fruit length, average fruit weight, and productivity. The average fruit length (cm) was determined by measuring the length of the fruit (pod), including the pod stalk, at harvest and then averaging the values. The average fruit weight (g) was calculated by dividing the total weight of fruits harvested from 10 tagged plants by the number of fruits produced by those same plants. Productivity (Mt/ha) was estimated by converting the net plot yield, measured from 10 tagged plants, into metric tons per hectare.

2.6 Statistical analysis

The data obtained from the experiment were analyzed using Microsoft Excel 2019 and R-Studio (version 4.5.2). Mean comparisons were performed using Duncan's Multiple Range Test (DMRT) and the Least Significant Difference (LSD) test at 5% level of significance (Gomez and Gomez, 1984).

3 Results and Analysis

3.1 Plant height (cm)

The mulching materials had a significant impact on plant height at 25, 40, and 60 days after sowing (DAS) (Table 1). At 25 DAS, the tallest plants (8.61 cm) were observed in plots mulched with black plastic; the leaf litter had the smallest plant height (5.89 cm). This treatment continued to produce the highest plant height at 40 days (22.37 cm) and 60 days (74.87 cm) after sowing. At 40 DAS, plant heights under mustard straw (20.17 cm) were statistically similar to those under black plastic mulch (22.37 cm). The leaf litter showed the lowest plant heights at 40 days (12.55 cm) and 60 days (53.97 cm). The results showed that black plastic mulch significantly increased plant height at all growth stages (25, 40 and 60 DAS), followed by mustard straw mulch, while leaf litter consistently resulted in the lowest plant heights throughout the growth period.

Table 1 Effect of mulching material on plant height of okra at East Rukum, Nepal, 2024

Treatments	25 DAS	40 DAS	60 DAS
Black plastic mulch	8.61[a]	22.37[a]	74.87[a]
Control	5.79[b]	15.60[bc]	61.17[bc]
Mustard straw	6.86[b]	20.17[ab]	68.82[ab]
Banmara	6.57[b]	16.57[bc]	62.97[bc]
Sawdust	6.08[b]	15.95[bc]	60.02[bc]
Leaf litter	5.89[b]	12.55[c]	53.97[c]
LSD (0.05)	1.41	5.12	11.06
SEM (±)	0.19	0.70	1.51
F-probability	0.005822**	0.01163*	0.01768*
CV%	14.31	19.98	11.65
Grand Mean	6.63	17.20	63.64

Note: LSD = Least Significant Difference; CV (%) = Coefficient of Variation; DAS = Days after sowing; SEM = Standard Error of the mean; Means followed by the same letter(s) within each column are not significantly different at 5% level of significance by DMRT, ** and * indicate significance at <0.01 level and significance at <0.05 level respectively

3.2 Leaf number

The mulching materials had a significant effect on leaf number at 25, 40, and 60 days after sowing (DAS) (Table 2). At 25 DAS, the highest number of leaves (5.48) was recorded in plots mulched with black plastic, whereas the lowest leaf number (4.51) was observed under banmara mulch. At this stage, all organic mulches and the control plot were statistically similar with respect to leaf number. At 40 DAS, black plastic mulch again produced the maximum leaf number (19.60). The control plot (14.58), mustard straw (13.48), and banmara mulch (14.28) were statistically comparable, while sawdust (9.98) and leaf litter (11.58) recorded the lowest leaf numbers. At 60 DAS, black plastic mulch (27.58) maintained the highest leaf number, while leaf litter resulted in the lowest leaf number (15.88). The control plot (20.58) and banmara mulch (20.78) showed statistically similar leaf numbers. Overall, the results indicated that black plastic mulch significantly increased leaf numbers at all growth stages (25, 40, and 60 DAS), followed by mustard straw and banmara mulches, whereas sawdust and leaf litter mulches consistently produced the lowest leaf numbers throughout the crop growth period.

Table 2 Effect of mulching material on leaf number of okra at East Rukum, Nepal, 2024

Treatments	25 DAS	40 DAS	60 DAS
Black plastic mulch	5.4750[a]	19.600[a]	27.58[a]
Control	4.9500[b]	14.58[ab]	20.58[ab]
Mustard straw	4.8000[b]	13.48[ab]	19.68[b]
Banmara	4.5125[b]	14.28[ab]	20.78[ab]
Sawdust	4.7125[b]	9.98[b]	17.40[b]
Leaf litter	4.6750[b]	11.58[b]	15.88[b]
LSD (0.05)	0.4837	5.962	7.091
SEM (±)	0.162	0.818	0.974
F-probability	0.0097*	0.05*	0.0449*
CV%	6.708	28.84	23.498
Grand Mean	4.85	13.91	20.31

Note: LSD = Least Significant Difference; CV (%) = Coefficient of Variation; DAS = Days after sowing; SEM = Standard Error of the mean; Means followed by the same letter(s) within each column are not significantly different at 5% level of significance by DMRT, ** and * indicate significance at <0.01 level and significance at <0.05 level respectively

3.3 Yield parameter and productivity

The results showed that the average fruit weight was highest (245.80 g) under black plastic mulch, which was significantly superior to mustard straw, banmara, sawdust, and leaf litter mulches, but statistically similar to the control plot (193.70 g) (Table 3). The lowest fruit weight (129.85 g) was recorded under leaf litter mulch. Average fruit length was also significantly affected by mulching. The longest fruits (14.91 cm) were obtained under black plastic mulch, followed by leaf litter (13.76 cm) and control plots (13.67 cm). The shortest fruits (12.88 cm) were recorded in mustard straw mulch. The productivity was highest under black plastic mulch (14.897 Mt/ha), followed by the control plot (11.739 Mt/ha), mustard straw (9.289 Mt/ha), banmara (9.831 Mt/ha), sawdust (8.433 Mt/ha), and leaf litter (7.87 Mt/ha), respectively. Increased productivity under black plastic mulch is likely associated with larger and longer fruits, higher fruit set, and improved microclimate conditions, leading to enhanced overall yield.

Table 3 Effect of mulching materials on yield parameters and productivity of okra at East Rukum, Nepal, 2024

Treatments	25 DAS	40 DAS	60 DAS
Black plastic mulch	245.80[a]	14.91167[a]	14.897[a]
Control	193.70[ab]	13.67250[ab]	11.739[ab]
Mustard straw	162.20[b]	12.87583[b]	9.289[b]
Banmara	153.25[b]	13.53425[b]	9.831[b]
Sawdust	139.15[b]	13.06667[b]	8.433[b]
Leaf litter	129.85[b]	13.76167[ab]	7.87[b]
LSD (0.05)	69.70379	1.199951	4.27
SEM (±)	9.537208	0.162517	1.41
F-probability	0.02674*	0.03556*	0.0307*
CV%	27.37785	5.838235	27.39
Grand Mean	170.6583	13.6371	10.343

Note: LSD = Least Significant Difference; CV (%) = Coefficient of Variation; DAS = Days after sowing; SEM = Standard Error of the mean; Means followed by the same letter(s) within each column are not significantly different at 5% level of significance by DMRT, ** and * indicate significance at <0.01 level and significance at <0.05 level respectively

4 Discussion

The result presented in Table 1 shows that black plastic mulch had the tallest plant height at 25 DAS, 40 DAS, and 60 DAS. These findings are in accordance with (Chaudhary et al., 2023), who reported the highest plant height under black plastic mulch at each stage. At the beginning of the growing season, the remaining treatments did not show significant differences in plant height. The improved growth under black plastic mulch can be attributed to the effective suppression of weeds, which reduces competition between weeds and crop plants (Bhutia et al., 2017). A direct relationship between plant height and soil residual moisture has been reported, where moisture stress reduces plant growth, while mulching helps maintain favorable conditions (Otuaro et al., 2024). Furthermore, mulching creates stable soil physical conditions that promote root expansion and enhance nutrient uptake, thereby contributing to improved plant growth (Kamble et al., 2020).

Black plastic mulch significantly influenced the leaf number of okra at 25, 40, and 60 DAS, consistently producing the highest number of leaves across all growth stages. This trend aligns with findings from recent studies showing that plastic mulches, especially black plastic, improved vegetative growth characteristics in okra and other vegetable crops, such as leaf number (Chaulagain et al., 2024). On the other hand, organic mulches such as sawdust and leaf litter exhibited lower leaf numbers, particularly at 40 and 60 DAS. The comparatively weaker performance of organic mulches may be due to their limited ability to modify soil temperature and moisture conditions in the short term, which are critical for rapid vegetative growth (Kim et al., 2016).

The superior performance of black plastic mulch can be more broadly attributed to its regulation of the soil microenvironment. Modifying the soil energy balance and limiting evaporative losses, it creates conditions that favor rapid leaf initiation and expansion (Thakur et al., 2020; El-Beltagi et al., 2022).

The fruit characteristics and productivity of okra were significantly influenced by mulching. Black plastic mulch produced the highest average fruit weight (245.80 g), fruit length (14.91 cm), and productivity (14.897 Mt/ha), whereas the lowest fruit weight (129.85 g) and productivity (7.87 Mt/ha) were recorded under leaf litter mulch. This yield advantage under black plastic mulch can be linked to cumulative effects on plant growth, rather than a single factor, resulting in improved fruit size and development.

The superior fruit length observed under black plastic mulch is consistent with earlier findings that plastic mulches enhance fruit elongation through improved soil moisture conservation and temperature regulation (Thakur et al., 2020). Similar improvements in pod length were reported by Singh et al. (2025) and Godawatte and De Silva (2016), who associated this response with improved growing conditions under mulch.

In contrast, organic mulches generally showed limited or inconsistent effects on productivity, which may reflect their slower modification of the soil environment and delayed nutrient availability (Thakur et al., 2020; Chaulagain et al., 2024), as also observed in the present study.

In contrast to the present study, Adhikari et al. (2023) and Smith and Onamadi (2021) reported higher okra yield under organic mulches, mainly due to reduced weed competition. This variation among studies indicates that environmental conditions, moisture availability, and management practices influence the effectiveness of mulching materials.

5 Conclusion

The findings of this study support that the black plastic mulch consistently outperformed other mulching materials in enhancing the growth and yield of okra under the agro-climatic conditions of East Rukum, Nepal. Plants grown with black plastic mulch exhibited greater plant height and higher leaf number at all growth stages compared to other treatments. This enhanced vegetative growth contributed to improved yield attributes, resulting in higher fruit weight and longer fruits. Consequently, black plastic mulch produced significantly higher productivity, while leaf litter mulch resulted in the lowest yield performance. Overall, the use of black plastic mulch was found to be the most effective mulching practice for improving the growth and productivity of okra.

Authors' contributions

Princess Magar conceived and designed the study, conducted the experiment, and collected the data. She also assisted with data analysis, statistical interpretation, and preparation of figures and tables. Jenisha Lama and Rakshya Devkota interpreted the results and contributed to manuscript writing. Jenisha contributed to the literature review and gathered relevant resources for manuscript development. Rakshya supervised the study, provided critical feedback, and improved the manuscript through suggestions and revisions. 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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Review and Progress Open Access

Current Status and Development Trends of Integrated Pest and Disease Management Technologies in Grapevine

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0010
Received: 12 Feb., 2026
Accepted: 30 Mar., 2026
Published: 28 Apr., 2026

Preferred citation for this article:
Li M.H., and Huang D.D., 2026, Current status and development trends of integrated pest and disease management technologies in grapevine, International Journal of Horticulture, 16(2): 105-121 (doi: 10.5376/ijh.2026.16.0010)

Abstract Grapevine is one of the most important fruit crops worldwide, but diseases such as downy mildew, powdery mildew, and gray mold, together with various insect pests, have long threatened its yield, quality, and the sustainable development of the industry. However, the traditional reliance on frequent chemical control has also led to resistance development, residue contamination, and ecological risks. This study systematically reviews the current status and development trends of integrated pest and disease management technologies in grapevine, with particular emphasis on the synergistic roles of agronomic regulation, biological control, resistant breeding, monitoring and early warning, precision spraying, and smart management. The results indicate that IPM, through threshold-based decision-making, multi-technology integration, and digital support, can reduce pesticide dependence and improve ecological benefits while ensuring yield and quality. Among these approaches, resistant cultivars, microbial and botanical products, decision support systems (DSS), as well as drones and Internet of Things technologies, have shown strong application potential. Overall, grapevine pest and disease management is shifting from chemical-dependent approaches toward precision-based, intelligent, and ecological strategies. This study provides a theoretical basis and practical reference for building a low-input, resilient, and sustainable modern grapevine protection system.
Keywords Grapevine (*Vitis vinifera* L.); Integrated pest and disease management; Integrated control; Biological control; Precision agriculture; Sustainable cultivation

1 Introduction

Grapevine (*Vitis vinifera* L.) is among the most important fruit crops worldwide, underpinning global wine, table grape, raisin, and juice industries and contributing substantially to rural livelihoods, export earnings, and cultural heritage in many regions (Pertot et al., 2017). Viticulture occupies millions of hectares and supports a high-value value chain from production through processing and tourism, making stable yields and consistent quality a strategic economic objective (Van Leeuwen et al., 2024). However, the crop is highly susceptible to a broad spectrum of pathogens and pests—fungi, oomycetes, bacteria, viruses, nematodes, and insects—that damage leaves, shoots, and clusters, with direct consequences for yield, fruit composition, and marketability (Pertot et al., 2017; Gawande and Sherekar, 2024). Downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), Botrytis cinerea gray mold, trunk diseases, and various insect pests remain the major phytosanitary constraints in most viticultural regions and can require numerous interventions each season to maintain quantitative and qualitative standards (Bois et al., 2017; Gawande and Sherekar, 2024; Van Leeuwen et al., 2024). As a result, pest and disease management is central to sustaining the productivity, profitability, and international competitiveness of grape industries.

Modern grape cultivation's heavy reliance on synthetic pesticides has created a series of agronomic, environmental, and social problems. In many regions, fungicides account for the majority of pesticide use in vineyards, and under high disease pressure, 12-15 spray applications are typically required during a single growing season, with the number sometimes reaching 25-30 (Pertot et al., 2017; Mwaka et al., 2024). Intensive or improper pesticide use has been shown to result in toxic residues in grapes, juice, and wine, while also causing soil and water contamination and negatively affecting biodiversity and human health (Mwaka et al., 2024;

Alimzhanova et al., 2025; Liviz et al., 2025). The excessive use of single-site fungicides and insecticides has accelerated the evolution of resistance in key pathogens such as *P. viticola* and other fungal pests, thereby increasing the difficulty of control and threatening the long-term effectiveness of existing active ingredients (Pertot et al., 2017; Mwaka et al., 2024; Toffolatti et al., 2024). Climate change is also altering the distribution patterns and pressure of pests and diseases. Diseases such as downy mildew have become major threats under a wide range of climatic conditions, and even greater challenges are expected by the middle of this century (Bois et al., 2017; Van Leeuwen et al., 2024).

Integrated pest management (IPM) has gradually become the central concept in grape protection. Its goal is to integrate agronomic practices, biological control, genetic improvement, and chemical measures in order to keep pest and disease pressure below economic thresholds while minimizing pesticide inputs and their associated risks (Pertot et al., 2017; Mwaka et al., 2024; Zhou et al., 2024). At present, vineyard IPM systems incorporate a wide range of strategies, including agronomic management such as canopy management, pruning, and vineyard sanitation; the use of disease-resistant cultivars; biological control agents and plant-derived products; pheromone disruption; spray decision-support systems; as well as precision agriculture and robotic technologies (Pertot et al., 2017; Aher et al., 2025). Resistant and tolerant cultivars, together with emerging breeding and genomic technologies such as marker-assisted selection and gene editing, provide important pathways for reducing fungicide use—by up to 80% in some cases—and for developing durable resistance (Trapp and Töpfer, 2023; Rahman et al., 2024; Gan et al., 2025). The development of organic, plant-derived, and microbe-derived control technologies has also shown potential for reducing pesticide dependence, improving soil health, and supporting organic or low-input production systems, although their formulation stability and field performance still require further optimization (Zhou et al., 2024; Alimzhanova et al., 2025). Despite the growing range of available technologies, their adoption remains uneven, and many growers still rely on calendar-based chemical control programs, with insufficient awareness of alternative approaches or problems such as grapevine trunk diseases.

This study aims to systematically review the current status and development trends of integrated pest and disease management technologies in grape production, with a particular focus on their role in balancing yield, quality, environmental sustainability, and food safety. By integrating multidimensional perspectives from agronomy, ecology, technology, and socioeconomics, this research seeks to establish a comprehensive framework that can provide guidance for growers, technical advisors, researchers, and policymakers, thereby supporting the implementation of more resilient and resource-efficient IPM strategies across diverse grape-growing regions.

2 Major Pests and Diseases in Grapevine

2.1 Common fungal and bacterial diseases

The most destructive fungal diseases in grape production mainly include downy mildew, powdery mildew, and gray mold. Downy mildew, caused by *Plasmopara viticola*, spreads readily under humid conditions and can infect leaves, young shoots, inflorescences, and grape clusters, leading to early defoliation and significant yield loss in severe cases (Capriotti et al., 2020; Koledenkova et al., 2022). Powdery mildew, caused by *Erysiphe necator*, can infect green tissues and berries even under relatively dry conditions, weakening photosynthesis and affecting fruit composition and wine flavor (Capriotti et al., 2020). Gray mold, caused by *Botrytis cinerea*, mainly damages flowers and ripening fruits, resulting in postharvest decay and quality deterioration (Rienth et al., 2021).

Among bacterial diseases, crown gall is the most important in grapevine and is mainly caused by *Allorhizobium vitis*, although it can also be induced by tumorigenic *Agrobacterium tumefaciens*. The pathogen transfers tumor-inducing DNA into host cells, causing galls to form on trunks, rootstocks, and graft unions, thereby disrupting vascular tissues, weakening vine vigor, and shortening plant lifespan. The disease is especially severe in young vineyards and in regions frequently affected by frost injury (Faist et al., 2016; Habbadi et al., 2023). Its management is particularly difficult because the pathogen can persist for long periods in both plant tissues and soil, while conventional chemical treatments have limited effectiveness. At present, the most effective measures still include the use of disease-free planting material, reduction of mechanical injuries and frost damage, selection of tolerant rootstocks, and biological control using non-tumorigenic *Agrobacterium* strains and antagonistic endophytes (Asghari et al., 2019; Etminani et al., 2024). In recent years, studies on the characteristic microbial communities associated with galls have also provided new ideas for crown gall diagnosis and microbiome-based control strategies (Nguyen-Huu et al., 2025).

2.2 Insect pests affecting grapevine

Grape phylloxera (*Daktulosphaira vitifoliae*) is one of the most representative pests in grape production. Native to North America, it primarily attacks the roots, forming galls on fine roots and nodose roots, which interfere with water and nutrient uptake and can also promote secondary infection by soil-borne pathogens. In severe cases, it may cause vine decline or even death (Yin et al., 2019). The phylloxera crisis in the nineteenth century devastated European vineyards and led to the adoption of resistant rootstocks as a core control strategy in grape production worldwide. However, because this pest has high genetic diversity and strong host adaptability, outbreaks may still recur when rootstock selection is inappropriate or when local biotypes overcome existing resistance.

Another important group of pests includes leafhoppers and other sap-sucking insects. These pests feed directly on xylem or leaf sap, weakening vine growth, and they also transmit several serious diseases, such as phytoplasmas associated with *Flavescence dorée* and *Xylella fastidiosa*, the causal agent of Pierce's disease (Reineke and Thiéry, 2016; Lessio and Alma, 2021). Because pathogen transmission is highly efficient and effective treatment is lacking once infection occurs, the economic losses caused by these pests are often greater than those caused by feeding damage alone. In practice, integrated control usually requires a combination of pest monitoring, phenological analysis, and agronomic, chemical, and biological measures.

Tortricid moths, leaf-feeding beetles, and other chewing pests also damage grape inflorescences, clusters, and leaves. Tortricid larvae can feed directly on fruit and create entry points for pathogens such as *Botrytis cinerea*, thereby further aggravating bunch rot and quality deterioration (Lessio and Alma, 2021; Alimzhanova et al., 2025). Leaf-feeding pests reduce effective leaf area by damaging leaves and young shoots, which in turn affects vine growth and fruit ripening (Singh and Acevedo, 2023). Current vineyard pest management places greater emphasis on integrated control, combining the use of plant defense traits with the conservation of natural enemies and habitat management to improve the stability of IPM systems (Singh and Acevedo, 2023; Alimzhanova et al., 2025).

2.3 Emerging and region-specific threats

Climate change is continuously reshaping the pattern of grape pest and disease occurrence. Rising temperatures, longer growing seasons, and more frequent extreme weather events can accelerate insect development, increase the number of generations per year, and drive the expansion of grape berry moths, mealybugs, leafhoppers, and other pests toward higher latitudes and elevations (Reineke and Thiéry, 2016). At the same time, downy mildew and powdery mildew are highly sensitive to temperature changes, and in many grape-producing regions, their epidemic risk may persist or even intensify in the future (Rienth et al., 2021; Koledenkova et al., 2022). Changes in climatic conditions may also promote the expansion of virus–insect transmission systems, further increasing the incidence of viral diseases such as leafroll disease, fanleaf disease, and red blotch disease (Rienth et al., 2021). These changes interact with regional differences in soil conditions, grape varieties, and management practices, creating marked geographic variation, and are often accompanied by the spread of invasive alien species.

With the acceleration of global trade in propagation materials and agricultural commodities, invasive vector insects such as leafhoppers and sharpshooters capable of transmitting *Xylella fastidiosa* and phytoplasmas are continually entering new production regions. Once established, these invasive species can rapidly create new epidemiological systems. For example, the spread of the glassy-winged sharpshooter in California has been closely associated with outbreaks of Pierce's disease in grapevines and other host crops (Reineke and Thiéry, 2016; Lessio and Alma, 2021). Similarly, differences in the damage caused by various phylloxera biotypes and by crown gall across regions also indicate that local climate and cultivation conditions can profoundly influence the epidemiological consequences of grape pests and diseases (Yin et al., 2019; Habbadi et al., 2023).

3 Conventional Control Methods in Grapevine Protection

3.1 Chemical control strategies

In grape production, chemical control has long been the core strategy for managing pests and diseases, particularly in the control of downy mildew, powdery mildew, and major insect pests. Commonly used fungicides include protective compounds such as copper- and sulfur-based products, as well as systemic or translaminar fungicides such as strobilurins, triazoles, and SDHI fungicides, which are typically applied at fixed intervals throughout the growing season (Pertot et al., 2017; Pennington et al., 2018; Moine et al., 2023). Insect control is generally implemented when pest populations exceed economic thresholds, using organophosphates, neonicotinoids, pyrethroids, and some newer selective insecticides to manage key pests such as grape moths and disease-transmitting leafhoppers (Mwaka et al., 2024; Pavan et al., 2026). Under intensive cultivation systems, multiple pesticide applications are required within a single growing season to maintain yield and fruit quality.

However, frequent and preventive chemical applications also bring several problems. First, the risk of resistance development increases. After long-term repeated use, single-site fungicides have already selected for resistant populations in pathogens causing downy mildew and powdery mildew, as well as in some insect pests, thereby reducing the effectiveness of these chemicals (Toffolatti et al., 2024; Kaya et al., 2025). Second, pesticide residue issues have attracted increasing attention. Residues not only affect the food safety of grapes, grape juice, and wine, but may also impact non-target organisms and fermentation-related microbial communities, thereby indirectly influencing wine quality (Liviz et al., 2025).

3.2 Cultural and agronomic practices

Agronomic and cultivation management constitute an important foundation of traditional grape protection systems. Their main purpose is to reduce primary inoculum sources and suppress the occurrence of diseases and pests by improving the vineyard microclimate. Pruning, shoot training, and canopy management can improve air circulation and light penetration, thereby reducing canopy humidity and limiting the development of diseases such as downy mildew, powdery mildew, and gray mold (Pertot et al., 2017; Testempasis et al., 2023). At the same time, the timely removal of infected branches, mummified clusters, and weed hosts within the vineyard can effectively reduce overwintering pathogens and the sources of primary infection in the following growing season. In recent years, the concept of “proper pruning” has also emphasized minimizing large wounds and protecting sap flow pathways in order to maintain the long-term health of the vine (Mondello et al., 2017).

Soil, water, and nutrient management also directly affect grape resistance and disease pressure. Cover crops, green manure, and soil surface management can improve soil structure, enhance water infiltration, and increase soil microbial diversity, thereby strengthening plant stress resistance (Perria et al., 2022). In contrast, excessive nitrogen application can lead to excessive vegetative growth and dense canopies, increasing vineyard humidity and consequently aggravating fungal diseases and the risk of cluster rot (Pavan et al., 2026). In addition, proper irrigation, timely water regulation, and practices such as leaf removal and fruit thinning can help reduce cluster rot and the probability of pathogen colonization, thereby improving the overall effectiveness of disease control (Testempasis et al., 2023).

3.3 Physical and mechanical control

Physical and mechanical methods provide additional, often pesticide-free, tools for managing grapevine pests and can be readily integrated into conventional programs. Traps, particularly pheromone traps, are widely used for monitoring grape moth flights and can guide the timing of insecticide applications, thereby reducing unnecessary sprays (Pertot et al., 2017; Pennington et al., 2018; Pavan et al., 2026). In some settings, mass trapping or attract-and-kill devices contribute to direct suppression of pest populations, although these techniques are generally more effective when pest pressure is moderate and landscapes are relatively isolated (Pertot et al., 2017; Pavan et al., 2026). Physical barriers such as insect-proof nets or inter-row ground covers can prevent some insects from entering the canopy, but large-scale structural modification of vineyards is often limited by economic costs and landscape conservation requirements, especially in traditional European wine-growing regions (Pertot et al., 2017). In addition, the manual removal of infested clusters, diseased leaves, or severely infected young shoots is still practiced in high-value or small-scale vineyards to reduce local pest and disease sources and to improve spray penetration and canopy ventilation (Pertot et al., 2017; Testempasis et al., 2023).

Environmental modifications for pest suppression, beyond standard canopy and irrigation management, include targeted manipulation of microclimate and habitat at the vineyard scale. Practices such as strategic defoliation and bunch thinning at specific phenological stages have been shown to reduce the incidence of bunch rots and mycotoxin-producing fungi by decreasing humidity around clusters and altering the composition of the berry-associated microbiota (Gutiérrez-Gamboa et al., 2021; Testempasis et al., 2023). Landscape-level decisions—choice of vineyard site, row orientation, training system, and surrounding vegetation—also influence pest and vector populations, their movement into vineyards, and the effectiveness of natural enemies (Pertot et al., 2017; Pavan et al., 2026).

4 Biological Control and Eco-friendly Approaches in Grapevine Management

4.1 Microbial control agents

Microbial biocontrol agents have become an important component of green disease management in grape production and have shown strong potential against downy mildew, powdery mildew, gray mold, and bunch rot. Commonly effective microorganisms include *Trichoderma*, *Bacillus*, *Aureobasidium pullulans*, and *Pseudomonas*, all of which can reduce disease incidence under field conditions. Some studies have reported control efficacies of 60%-90% (Thiéry et al., 2018; Alimzhanova et al., 2025). Yeasts and microbial consortia also show advantages in suppressing gray mold and improving fruit quality, and they have demonstrated good control effects against trunk diseases such as Botryosphaeria dieback during the nursery stage (Leal et al., 2022; Mesguida et al., 2023).

These microorganisms act through multiple mechanisms, including competition for nutrients and space, secretion of antimicrobial compounds and degradative enzymes, parasitism of pathogen structures, and competition for key elements through siderophore production, thereby directly inhibiting pathogen growth (Compant et al., 2013). Some strains can also induce systemic resistance (ISR) in plants, activate defense-related signaling pathways, and enhance the overall resistance of grapevines to multiple diseases. As reported by Lakkis et al. (2019), using the grapevine cultivars Pinot Noir and Solaris as study materials, the differential mechanisms of resistance induced by the beneficial rhizobacterium *Pseudomonas fluorescens* PTA-CT2 were investigated. The results showed that this bacterium could enhance the plant's own defense capacity through a "priming" effect. Against downy mildew, it mainly activated the SA-related signaling pathway and induced a more pronounced hypersensitive response (HR) in Solaris. Against gray mold, however, resistance relied more on JA/ET signaling and was associated with suppression of excessive cell death (Figure 1). Although microbial biocontrol agents have clear advantages such as environmental friendliness, their efficacy still varies across regions and years, and there is still room for improvement in formulation stability and environmental adaptability.

4.2 Natural enemies and biological regulation

Natural enemy regulation is a key component of ecological pest management in vineyards and plays an important role in suppressing pests such as grape moths, leafhoppers, and mealybugs. Vineyards host diverse communities of predators and parasitoids, including hymenopteran parasitoids attacking grape moths, lacewings such as Chrysoperla externa, spiders, predatory mites, and vertebrates such as insectivorous birds and bats. Under appropriate management conditions, these natural enemies can reduce pest populations and crop damage (Thiéry et al., 2018; Korányi et al., 2025). Studies on grape moth control have shown that parasitoids and predators can exert strong suppression at the local scale, although their effectiveness depends on specific ecological conditions and remains underutilized compared with chemical control and pheromone disruption techniques (Thiéry et al., 2018).

Recent field exclusion experiments have demonstrated that birds and bats can reduce leaf-feeding damage and injury caused by *Lobesia botrana*. In landscapes connected to forests, bat activity is more frequent and is closely associated with reduced moth populations and increased yields (Korányi et al., 2025). For grape mealybugs, refuge plant studies conducted in Peru have shown that planting flowering species to attract beneficial arthropods such as *Chrysoperla externa* can effectively enhance the natural regulation of Planococcus pests (Cocco et al., 2020).

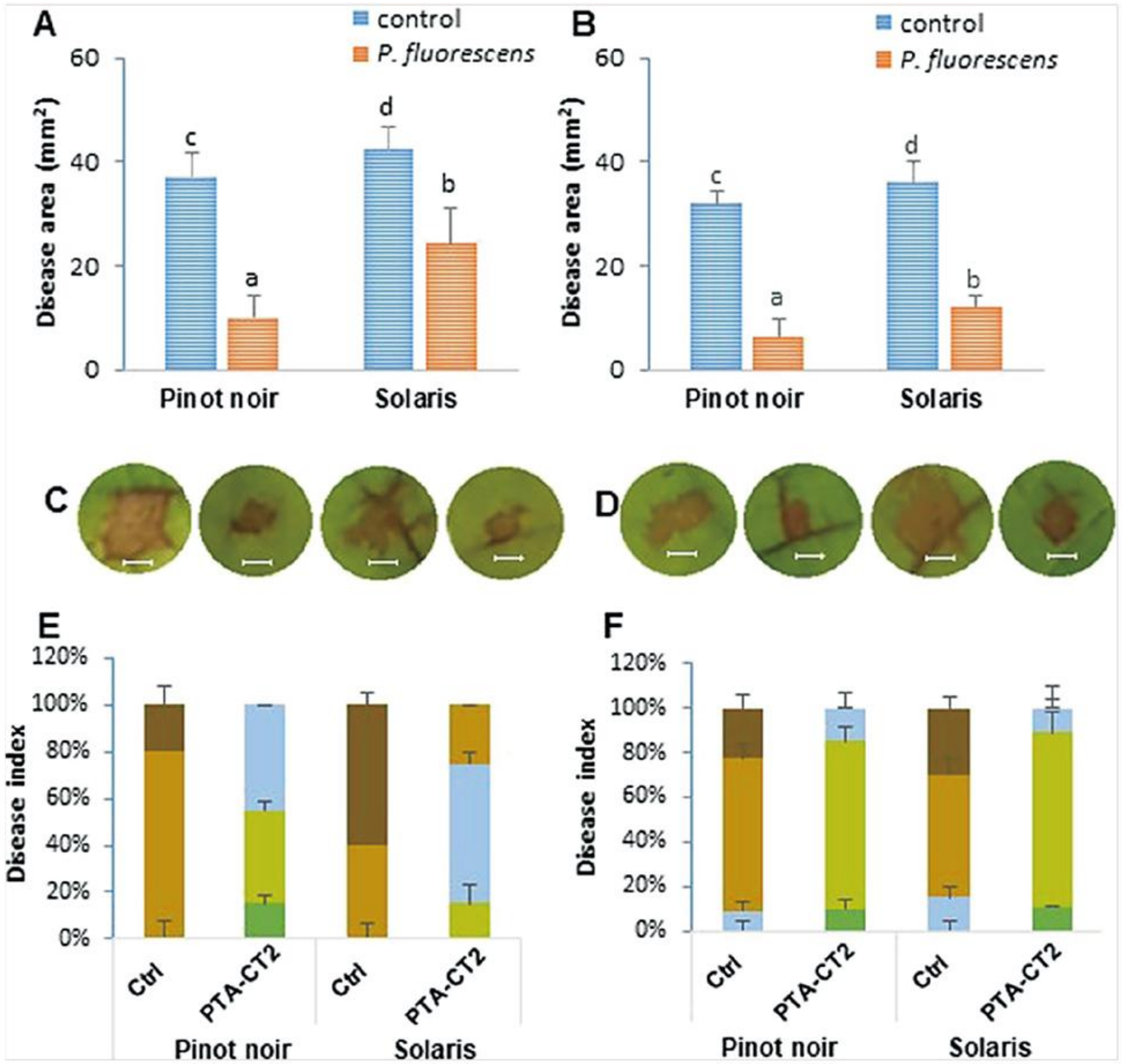

Figure 1 *Pseudomonas fluorescens* PTA-CT2 induces systemic resistance against *Botrytis cinerea* in Pinot noir and Solaris cultivars. Plants were treated at the root level with *P. fluorescens* at 10^7 CFU g^{-1} of soil. Two weeks later, leaf disks were collected from the upper third and fourth leaves and inoculated with 5 µl of 10^6 conidia ml^{-1} of *B. cinerea*. Necrotic lesion area was measured at 7 dpi with Compu Eye, Leaf & Symptom Area software (A, B). Panels C and D show representative disease symptoms on control and PTA-CT2-treated leaf disks at 7 dpi. Bars = 4 mm. Disease index (E, F) shows the proportion of leaf disks in symptom classes ranging from no visible symptom to lesions larger than 40 mm^2. Data are means from three independent experiments with 30 leaves per condition in 2016 (A, C, E) and 2017 (B, D, F); error bars indicate standard deviation. Different letters indicate significant differences among treatments (ANOVA Tukey test, $P < 0.05$) (Adopted from Lakkis et al., 2019)

The key to conservation biological control lies in optimizing habitat management. Maintaining inter-row vegetation, alternating mowing, and establishing flowering strips can provide food resources and shelter for parasitoids, lacewings, and spiders, thereby increasing their populations and pest control capacity (Cargnus et al., 2024). At the same time, surrounding forests and semi-natural habitats help attract birds and bats, strengthening predation pressure on pests such as grape moths (Korányi et al., 2025). However, intensive pesticide use can weaken the effects of natural enemies. Therefore, within an IPM framework, pesticide reduction, vegetation management, and habitat optimization should be integrated to achieve more stable biological regulation (Tortosa et al., 2025).

4.3 Botanical and biopesticides

Plant-derived products, including plant extracts and essential oils, are increasingly becoming important tools in the green management of grape diseases and are considered viable alternatives to some synthetic fungicides. Studies have shown that essential oils from thyme, rosemary, eucalyptus, lavender, and cinnamon can inhibit the growth of key grape pathogens, and when combined with reduced doses of copper-based products under field conditions, they can effectively reduce disease incidence (Kenfaoui et al., 2023; Alimzhanova et al., 2025). Among them, some essential oils can achieve inhibition rates exceeding 80% against pathogens associated with grapevine trunk diseases, and their control efficacy in woody tissues may even exceed 90%, indicating strong potential for managing trunk diseases, downy mildew, powdery mildew, and bunch rot (Kenfaoui et al., 2023). These products offer advantages such as biodegradability, low residue levels, and suitability for organic production systems, although their effectiveness is still influenced by pathogen type, the composition of active compounds, and environmental conditions.

Current developments in biopesticides are no longer limited to crude plant extracts but are gradually shifting toward more stable formulations and resistance-inducing products. Chitosan is a representative example, as it not only exhibits direct antimicrobial activity but also induces immune responses in grapevines, showing good control efficacy against downy mildew and powdery mildew (Brulé et al., 2024). Overall, although plant-derived and microbe-derived products have clear advantages in terms of environmental safety and pesticide reduction, they still face challenges such as limited stability, relatively short persistence, and variable field performance. Future efforts should focus on improving formulation technologies, developing combined products, and integrating them with precision application and decision-support systems to further enhance their role in integrated grape protection systems (Thiéry et al., 2018; Hajji-Hedfi et al., 2025).

5 Integrated Pest and Disease Management (IPM) Strategies in Grapevine

5.1 Principles and framework of IPM

In grape production, IPM is regarded as a systematic management framework whose core aim is to integrate agronomic, biological, physical, and chemical measures in order to keep pests and diseases below economically damaging levels while minimizing risks to human health and the environment (Pertot et al., 2017; Zhou et al., 2024). Its basic principle is to prioritize prevention through rational vineyard design and cultivation management, rely on natural regulation and biological control, and use pesticides selectively only when necessary as a last resort (Pertot et al., 2017; Pavan et al., 2026). Modern grape IPM emphasizes replacing and reducing the use of synthetic pesticides through resistant or tolerant cultivars, biological control, mating disruption, and optimized agronomic practices such as canopy management, ground cover, and vineyard sanitation, while establishing an integrated management system at both vineyard and landscape scales (Pertot et al., 2017; Wilson and Daane, 2017; Pavan et al., 2026). This multilevel integration is dynamic and regionally adaptable, allowing growers to gradually introduce new technologies and move from low-input IPM toward highly bio-intensive IPM systems (Barzman et al., 2015; Deguine et al., 2021).

One of the central pillars of this framework is threshold-based decision-making, meaning that control measures are implemented only when pest or disease levels, or predicted risks, exceed economic and agronomic thresholds (Lessio and Alma, 2021; Bashyal et al., 2022). Economic thresholds are determined by combining pest density, infection risk, crop growth stage, and expected yield loss, and are increasingly being incorporated into decision support systems (DSS) and predictive models (Pertot et al., 2017; Román et al., 2021; Bregaglio et al., 2022). The European Union’s eight IPM principles explicitly require monitoring, the use of warning systems, and the prioritization of non-chemical control measures, thereby translating the threshold concept into practical standards at the institutional level (Bregaglio et al., 2022). In grape production, these thresholds are usually combined with field observations and model outputs, such as downy mildew risk levels and pest phenology models, to help growers move away from fixed-calendar spray programs and adopt risk-based precision management strategies that balance control efficacy with environmental impact (Figure 2).

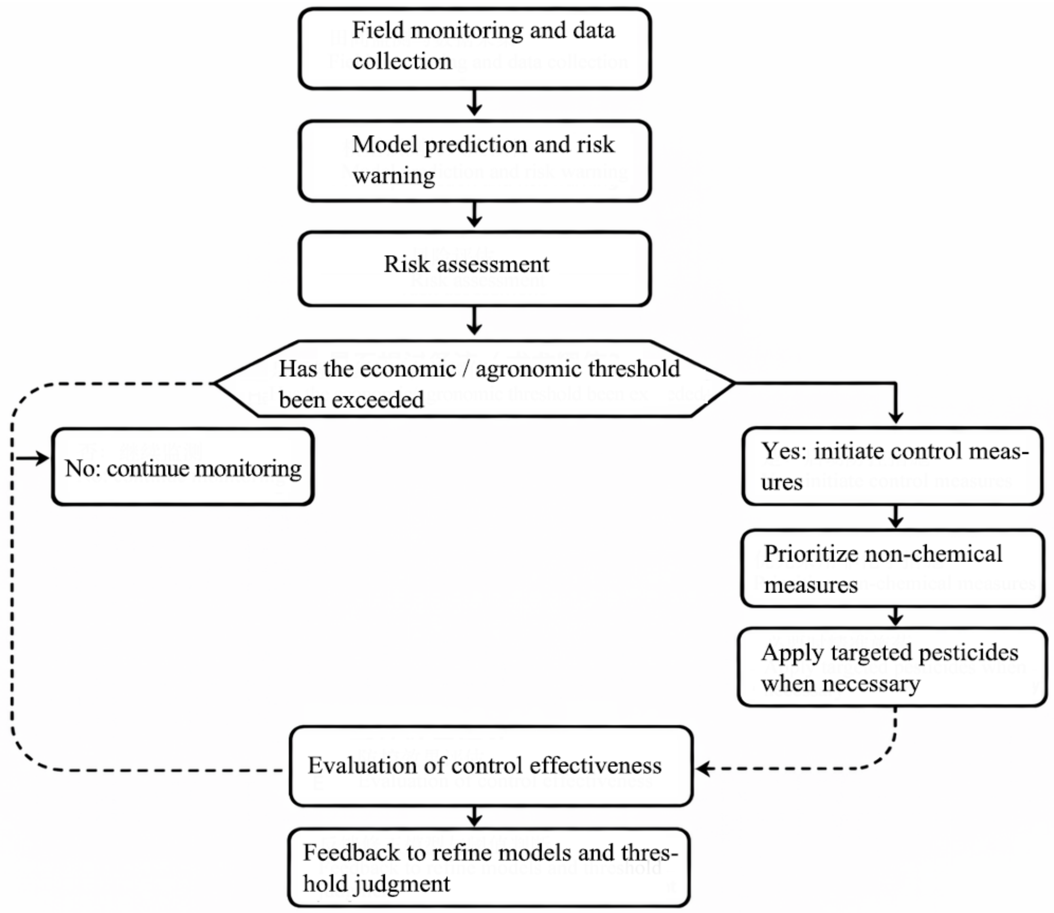

Figure 2 IPM decision flowchart based on economic thresholds

5.2 Monitoring and early warning systems

Field surveys remain the foundation of grape IPM, as they provide direct information for assessing pest and disease occurrence, crop growth stages, and the activity of natural enemies. Through standardized and regular monitoring—including sampling surveys of insects and mites as well as standardized disease assessment methods—it is possible to accurately determine pest and disease status and provide a basis for threshold application and DSS-based decision-making (Lessio and Alma, 2021; Bashyal et al., 2022). For leafhoppers, grape moths, and vector insects that transmit yellows diseases or Pierce's disease, monitoring usually combines trap surveillance with visual inspection of leaves and clusters, supported by predictive models to analyze their population dynamics (Pavan et al., 2026). In many IPM systems, plant protection services or grower organizations establish regional monitoring networks to integrate data from multiple farms and issue risk warnings and management recommendations, thereby enabling area-wide coordinated control and reducing unnecessary pesticide applications.

In recent years, monitoring technologies have evolved into warning systems that integrate field surveys, model analysis, and digital platforms. For example, in the management of grape downy mildew, the MISFITS system developed in Italy combines meteorological data, infection process models, grape phenology simulation, and machine-learning classification algorithms to divide infection risk into five levels, thereby achieving high-precision forecasting and guiding regional spray decisions (Bregaglio et al., 2022). In pest management, phenology and population dynamics models for grape moths, leafhoppers, mealybugs, and vector insects are also being progressively incorporated into DSS platforms to predict key developmental stages and outbreak risks (Lessio and Alma, 2021). These systems translate complex epidemiological and entomological knowledge into practical decision rules, enabling growers to identify risk windows in advance, optimize spray timing, and, when conditions permit, reduce or even omit control measures (Pertot et al., 2017; Román et al., 2021).

5.3 Integration of control technologies

In practical production, grape IPM relies on the coordinated application of multiple technologies rather than the isolated use of a single measure. Studies have shown that chemical pesticides (fungicides, herbicides, and insecticides) remain important components, but their use can be reduced by integrating biological control, mating disruption, resistant cultivars, as well as agronomic and physical measures (Zhou et al., 2024; Pavan et al., 2026). Cultivation practices—such as the selection of cultivars and rootstocks, training systems, pruning, fertilization, and irrigation—have a decisive influence on pest populations and disease pressure, and can simultaneously affect multiple pests and pathogens (Wilson and Daane, 2017; Pavan et al., 2026). Biological control agents and organically compatible products are increasingly combined with reduced chemical inputs to form hybrid strategies that balance efficacy and environmental safety (Pertot et al., 2017; Alimzhanova et al., 2025). For example, combining reduced fungicide use with resistance-inducing biostimulants or biocontrol agents can maintain control efficacy close to conventional programs while improving sustainability indicators (Pertot et al., 2017; Valleggi et al., 2023).

Within these integrated strategies, optimizing the timing and method of application is particularly important. For instance, the DOSA3D system adjusts pesticide dosage according to canopy structure and target pests or diseases, achieving up to approximately 60% reduction in pesticide use by matching leaf area index and spray efficiency without compromising crop health (Román et al., 2021). The application of robotics and sensor technologies further enhances precision: modular robots equipped with multispectral imaging can identify powdery mildew lesions and spray only infected areas, reducing pesticide use by 65%-85% compared with conventional uniform spraying (Oberti et al., 2016). In addition, predictive DSS systems allow growers to concentrate control measures during high-risk periods and reduce or avoid spraying during low-risk periods, aligning interventions more closely with pathogen biology and host susceptibility (Pertot et al., 2017; Román et al., 2021).

With the development of AIoT and computer vision technologies, real-time monitoring systems for diseases and vectors are gradually being applied in practice. These technologies are expected to further optimize the timing of interventions and enable data-driven, site-specific management, promoting grape IPM toward greater precision and intelligence while maintaining stable and efficient protection with reduced chemical inputs (Checola et al., 2024).

6 Case Studies of Grapevine IPM Applications

6.1 IPM implementation in European vineyards

In European viticulture, large-scale projects and regional practices have demonstrated that integrated pest management strategies can reduce pesticide use without compromising yield. The European PURE project showed that, in grape production, some application programs based on synthetic fungicides and insecticides can be partly replaced by biological control agents, mating disruption techniques, and decision support systems (DSS) that optimize spray timing, thereby reducing the overall number of applications (Pertot et al., 2017). At the same time, IPM frameworks in European vineyards emphasize that intervention decisions should be based on monitoring data and economic thresholds, with agronomic management and biological control prioritized, while synthetic pesticides are retained as a last resort, thus effectively limiting chemical inputs (Figure 3) (Pertot et al., 2017; Galli et al., 2024). In addition, landscape-scale management strategies, such as the conservation or restoration of semi-natural habitats, can enhance the role of natural enemies in pest suppression and reduce dependence on insecticides, particularly in the control of pests such as Lobesia botrana (Pertot et al., 2017; Korányi et al., 2025).

Comparative studies of organic and IPM vineyards in Europe further indicate that integrated management can maintain effective control of diseases and weeds while reducing overall toxic load and avoiding some of the limitations associated with strictly organic systems. In Swiss vineyards, long-term use of herbicides and copper-based fungicides has been shown to alter the structure of soil bacterial, fungal, and protist communities and to reduce soil microbial respiration, highlighting the ecological costs of intensive pesticide use (Steiner et al., 2024). In contrast, IPM systems based on limited and targeted pesticide applications are more likely to prevent severe disease outbreaks while reducing these unintended ecological impacts. Research in Hungarian vineyards has also shown that when IPM is combined with surrounding forest cover, which promotes the activity of natural enemies such as birds and bats, strong pest suppression can still be maintained even at lower levels of insecticide input, keeping moth damage to fruit at relatively low levels (Korányi et al., 2025). These studies indicate that integrated management strategies can reduce pesticide dependence while improving the overall functioning of vineyard ecosystems.

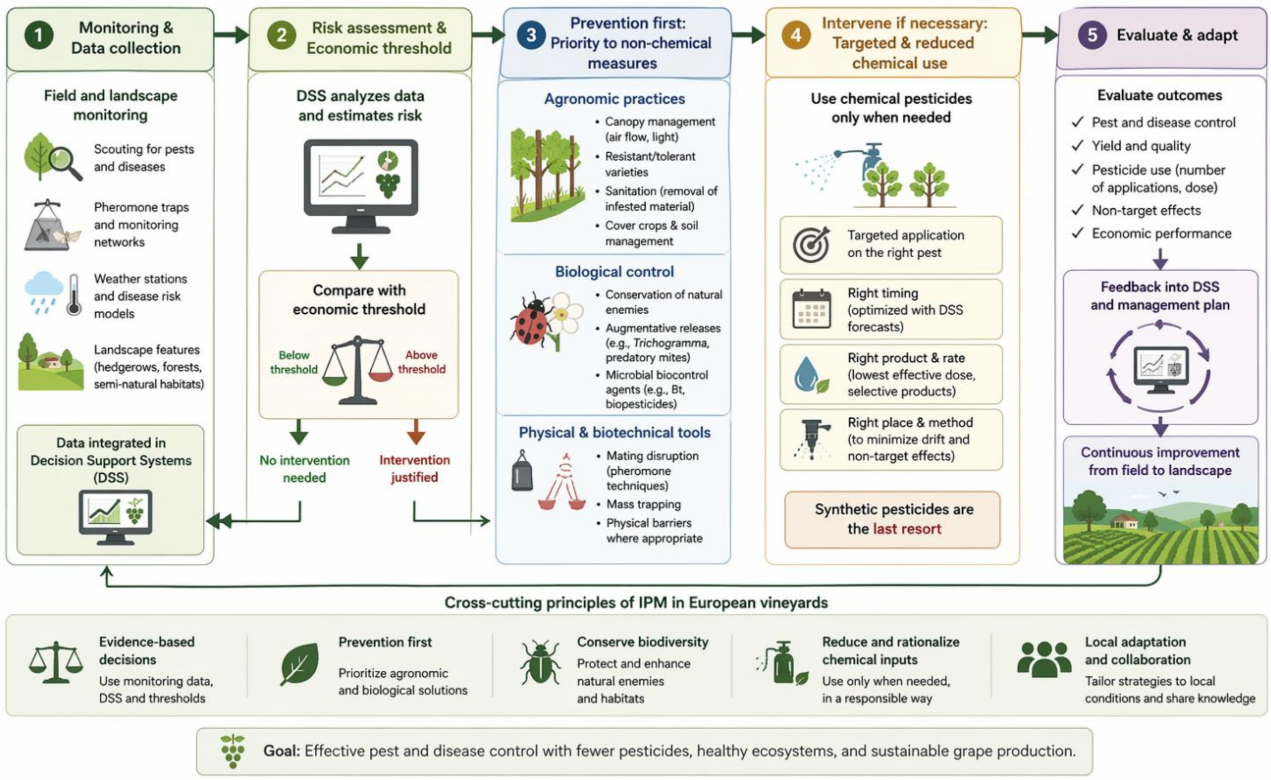

Figure 3 IPM implementation framework in European vineyards

Image caption: This figure outlines the IPM workflow in European vineyards, including monitoring, threshold-based decisions, prevention-first measures, necessary intervention, and evaluation, highlighting the roles of DSS, biological control, and targeted pesticide use in reducing chemical inputs

6.2 Smart vineyard management systems

Smart vineyard management systems are gradually becoming an important complement to traditional IPM, especially in precision viticulture, where they show clear advantages. IoT-based sensors, wireless networks, and remote sensing platforms can now provide real-time, high-spatial-resolution data on microclimate, soil moisture, plant status, and pest and disease indicators (Fuentes-Peñailillo et al., 2024; Mansoor et al., 2025). In a case study of precision viticulture in southern Italy, researchers combined IoT-based monitoring of weather and soil parameters with machine learning models to predict grape diseases, optimize water management, and reduce frost damage, demonstrating that this technology is not only feasible but also brings significant agronomic benefits

(Pero et al., 2024). From a broader application perspective, IoT-assisted smart traps and crop health sensors can enable the early detection of pests and diseases, thereby supporting targeted interventions, reducing pesticide use, and better reflecting the core principles of IPM (Mansoor et al., 2025).

Data-driven pest and disease management further builds on these sensing systems and artificial intelligence technologies, driving a transformation in IPM decision-making. AIoT platforms designed for vineyards can integrate field sensors, cloud computing, and machine learning algorithms to predict the infection risks caused by major pathogens such as *Plasmopara viticola*, *Uncinula necator*, and *Botrytis* spp., allowing growers to take action before symptoms appear and thereby avoid the traditional calendar-based practice of broad-area spraying (Fuentes-Peñailillo et al., 2024; Pero et al., 2024). In broader agricultural applications, deep learning models connected to IoT networks have already shown high accuracy in plant disease identification, helping to enable precise, site-specific pesticide application and optimize the timing of control measures (Fuentes-Peñailillo et al., 2024). Research on smart sensors and agricultural IoT has shown that real-time analysis and threshold-based warning functions can be embedded into farm management software, transforming complex data streams into actionable IPM recommendations while also supporting the coordinated optimization of irrigation and fertilization management (Ali et al., 2023; Mansoor et al., 2025). As these technologies become more accessible, “smart IPM” in viticulture is likely to drive pest and disease management toward greater localization, predictive capacity, and resource efficiency.

7 Emerging Technologies and Development Trends in Grapevine Protection

7.1 Genomic and breeding approaches

Breeding disease-resistant grape cultivars is one of the core directions for future grape protection, offering significant potential to reduce reliance on fungicides. After more than a century of breeding efforts, numerous fungus-resistant varieties (commonly referred to as PIWI types) have been developed, which, depending on the cultivar and environmental conditions, can reduce fungicide use by up to 80% (Trapp and Töpfer, 2023). Multinational trials conducted in France and Germany have shown that some resistant cultivars can even reduce fungicide applications by approximately 90%, while also enhancing arthropod diversity and overall vineyard biodiversity (Trapp et al., 2025). These cultivars are gradually being incorporated into the European Union’s Green Deal and Farm to Fork strategies aimed at pesticide reduction, and are considered important tools for addressing climate change and advancing smart viticulture.

Building on this, rootstock breeding and selection further enhance stress tolerance, including improved resistance to drought, soil-borne pests and diseases, and other belowground stresses, which is particularly critical under future climate change scenarios (Marín et al., 2020). Genomic technologies are now being fully integrated into breeding programs. Marker-assisted selection (MAS) has been widely applied to traits controlled by major genes, such as resistance loci for downy mildew and powdery mildew, while high-resolution melting (HRM)-based marker systems enable rapid screening of quality traits such as fruit color (Magon et al., 2023; Luca et al., 2024). For complex traits, including stress resistance, yield, and quality, genomic selection (GS) and predictive genomics show even greater potential, with prediction accuracies reaching up to 0.9 for certain traits, thereby enabling early selection and shortening breeding cycles (Magon et al., 2023; Brault et al., 2024). Combined with genome-wide association studies (GWAS), germplasm resources, and gene-editing technologies such as CRISPR/Cas9, these approaches are expected to facilitate the development of “climate-smart” grape cultivars with combined resistance to diseases and tolerance to drought, heat, or cold (Magon et al., 2023). At present, gene editing targeting susceptibility genes and stress-response pathways has already shown progress in improving grape cold and drought tolerance, and is expected to complement conventional breeding strategies in the future (Magon et al., 2023).

7.2 Digital and precision agriculture technologies

Digital technologies are rapidly transforming pest and disease monitoring and decision support in vineyards. Artificial intelligence-based image analysis, combined with mobile devices and online platforms, has already been used to automatically identify and count key pests in traps, as exemplified by the EyesOnTraps system in grape production (Rosado et al., 2022). This system integrates computer vision, temperature sensors, trap geolocation, and phenological models, such as the degree-day model for the European grapevine moth, into an operational decision support system (DSS), improving the precision of pest management while reducing the labor costs of manual monitoring. In addition, smartphone-based citizen science tools use deep learning algorithms to identify leaf diseases and insect pests, demonstrating the feasibility of real-time diagnosis and data collection at the farm scale (Christakakis et al., 2024). AI and deep learning, combined with unmanned aerial vehicles (UAVs) and ground-based imaging, have become an important foundation of smart agriculture, enabling the classification, segmentation, and prediction of pests and diseases from complex visual information (Zhu et al., 2024).

UAVs and advanced sensing technologies are also playing an increasingly important role in grape health monitoring. UAV systems equipped with RGB, multispectral, and hyperspectral sensors can be used to detect and map grape phylloxera infestation zones, and can be combined with canopy vigor models and vegetation indices to build predictive monitoring tools (Vanegas et al., 2018). Multi-temporal UAV multispectral imaging can also be used to monitor the development of downy mildew, identify early symptoms at both plot and individual vine scales, and track changes in canopy structure as well as near-infrared and red-edge reflectance (Portela et al., 2025). Kouadio et al. (2023) showed that grapevine is one of the crops most intensively studied for UAV-based disease detection, and that the current trend is toward multisensor fusion and machine learning analysis to improve detection accuracy and practical application value. Remote sensing and proximal sensors are also used to monitor vineyard microclimate, soil moisture, and canopy status, thereby supporting precision irrigation, frost protection, and microclimate regulation, which indirectly reduces disease risk and optimizes pest and disease management strategies (Sun et al., 2023).

7.3 Sustainable and climate-resilient strategies

Climate change is reshaping the pattern of grape pests and diseases and is accelerating the development of climate-adaptive management strategies. Rising temperatures, more frequent heat waves, and changing precipitation patterns are altering grape phenology, and in many regions have already advanced harvest time by 2-3 weeks. These changes are also modifying the pressure exerted by pathogens and insect pests, and some traditional wine-growing regions are expected to face severe drought and heat stress by the end of this century (Van Leeuwen et al., 2024). Global-scale analyses indicate that, under climate warming, the synchrony between grapevines and key pests such as Lobesia botrana is changing, which may lead to an increase in pest generations or shifts in the timing of damage.

In response to these changes, adaptation strategies in viticulture include replacing cultivars and rootstocks, promoting drought- and heat-tolerant materials, and optimizing training systems and canopy management to reduce heat load and improve microclimatic conditions that are favorable to disease development (Marín et al., 2020; Van Leeuwen et al., 2024). At the same time, the integration of artificial intelligence-based warning systems and smart agriculture sensors can help growers respond in advance to extreme weather events and climate-driven disease risks (Van Leeuwen et al., 2024).

From a broader perspective, sustainable ecological cultivation provides systemic support for these technologies. Studies in Mediterranean and semi-arid regions have shown that combining deficit irrigation strategies, such as regulated deficit irrigation and partial root-zone drying, with agroecological practices, including cover crops, mulching, compost application, reduced tillage, and the promotion of beneficial microbial interactions, can improve water-use efficiency, enhance soil health, and strengthen plant stress tolerance, while maintaining or even improving fruit quality (Romero et al., 2022). These measures help mitigate drought and heat stress, while also reducing erosion and nutrient loss and supporting natural enemy populations, thereby achieving the dual goals of climate adaptation and pesticide reduction (Marín et al., 2020). The wider adoption of disease-resistant cultivars, especially in the context of the European Green Deal, will further reduce fungicide use, enhance biodiversity, and improve the ecological functioning and long-term sustainability of vineyard systems (Trapp and Töpfer, 2023).

8 Conclusions and Future Perspectives

Current grape pest and disease management is shifting from a model based on sole reliance on chemical pesticides toward an integrated approach that combines multiple control measures. Agronomic management, disease-resistant cultivars, biological control agents, decision support systems (DSS), and more judicious chemical control have become the main tools in grape protection. Combining agronomic regulation, biological control, genetic resistance, and targeted spraying can maintain yield and quality while reducing pesticide inputs and improving the vineyard ecological environment. Some case studies have also shown that combined measures such as reduced-copper programs, resistance inducers, and predictive models are feasible in practical production.

However, in reality, chemical control remains the basic strategy in most vineyards, and total pesticide use has not declined despite the wider adoption of IPM concepts. This is related not only to insufficient policy support and the inadequate application of ecological regulation mechanisms, but also to factors such as growers' awareness, upfront investment, labor requirements, and concerns about production risks. The adoption rates of virus disease management, biological control, and more complex integrated technologies are still relatively low. Difficult access to forecasting tools, insufficient precision in pesticide application, and the high cost of alternative technologies have also limited the effectiveness of implementation. The development of new technologies is also relatively fragmented. Genomics, RNA interference, nanodelivery systems, smart sensors, drone-based monitoring, and advanced DSS are still progressing largely in parallel and have not yet formed a highly coordinated and efficient integrated system.

Future research should focus on improving the stability and substitution potential of non-chemical control technologies so that they can truly serve as major supports for pesticide reduction or even replacement. Plant-derived and microbe-derived biopesticides, nanodelivery systems, and RNA interference technologies show strong promise for controlling major pathogens, but their industrial application still requires large-scale field validation, formulation optimization, and cost reduction. At the same time, breeding cultivars with durable resistance to downy mildew, powdery mildew, gray mold, trunk diseases, and viral diseases through marker-assisted selection, genomic selection, and CRISPR technologies will also reduce the need for chemical intervention at the source. More research in agroecology is also needed, especially through the use of cover crops, vegetation diversification, and semi-natural habitat management, in order to strengthen the natural regulatory capacity of vineyards.

Future grape protection will increasingly depend on interdisciplinary integration. Internet of Things sensors, drone imaging, and artificial intelligence-based decision platforms are expected to improve the coordination of monitoring, forecasting, and precision spraying, but this will require the establishment of a closed-loop system from sensing to action, as well as stable operation under complex environmental conditions. At the same time, socioeconomic and behavioral factors should not be overlooked. Policy support, technical training, and participatory extension are needed to lower the barriers for growers to adopt new technologies. In response to climate change, invasive pests, and the increasing emergence of new pathogens, future grape pest and disease management must move toward a more forward-looking, biosecurity-oriented, and system-integrated direction, ultimately building a modern grape production system that is low-input, highly resilient, and sustainable.

Acknowledgments

The authors would like to express their sincere gratitude to Ms. Li for her assistance in organizing the literature materials. The authors also extend special thanks to the two anonymous peer reviewers for their comprehensive evaluation of the 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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International Journal of Horticulture, 2026, Vol.16, No.2, 122-134
http://hortherbpublisher.com/index.php/ijh

Review Article Open Access

Influence of Plant Growth Regulators on Eggplant Yield and Uniformity

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International Journal of Horticulture, 2026, Vol.16, No.2 doi: 10.5376/ijh.2026.16.0011
Received: 20 Feb., 2026
Accepted: 02 Apr., 2026
Published: 30 Apr., 2026

Preferred citation for this article:
Li Z.G., and Wu W.C., 2026, Influence of plant growth regulators on eggplant yield and uniformity, International Journal of Horticulture, 16(2): 122-134 (doi: 10.5376/ijh.2026.16.0011)

Abstract Eggplant production often faces problems such as unstable fruit set, yield fluctuation, and poor fruit uniformity. Plant growth regulators have therefore become an important regulatory tool for improving commercial production efficiency. This study discusses the effects of plant growth regulators on eggplant yield and uniformity, with particular emphasis on their roles in promoting flowering and fruit set, increasing fruit number per plant, improving single-fruit weight, and enhancing fruit shape and ripening synchrony. The results indicate that regulators such as GA_3 and NAA can significantly improve yield components, whereas 6-BA, SA, and EBR are more effective in alleviating abiotic stress, maintaining growth continuity, and enhancing fruit uniformity. Overall, plant growth regulators can achieve coordinated improvements in yield increase, yield stability, and quality enhancement when applied at appropriate concentrations and developmental stages. This study provides a theoretical basis and practical reference for precision cultivation of eggplant, the scientific application of growth regulators, and the management of commercial production.
Keywords Eggplant; Plant growth regulators; Yield; fruit uniformity; Fruit set rate; Stress regulation

1 Introduction

Eggplant (*Solanum melongena* L.) ranks among the most economically important solanaceous vegetables, after crops like tomato and potato, and is widely cultivated across tropical and temperate regions (Oladosu et al., 2021; Shi et al., 2023). Large germplasm collections and active breeding programs underscore its global significance for food systems and markets (Oladosu et al., 2021). Demand is rising due to its culinary versatility, nutritional value, and year-round availability, yet regional production often remains below potential because of land, climate, and management constraints (Alicja et al., 2019; Rathore et al., 2022).

For both consumers and producers, yield, fruit size, shape, and external appearance are key agronomic and commercial traits (Taher et al., 2017; Alicja et al., 2019). Uniform fruit length, diameter, weight, and shape improve grading, packaging, and price, while non-uniformity leads to higher discard rates and economic loss (Wakchaure et al., 2020; Rathore et al., 2022). Environmental stresses, nutrient imbalances, and irregular fruit set frequently compromise both total yield and fruit uniformity (Wakchaure et al., 2020; Rathore et al., 2022).

Plant growth regulators are organic compounds, distinct from nutrients, that regulate plant growth and development at very low concentrations (Bons and Kaur, 2019; Zahid et al., 2022; Amin et al., 2025). They include endogenous hormones and synthetic analogues such as auxins, gibberellins, cytokinins, ethylene, abscisic acid, brassinosteroids, jasmonates, and salicylic acid (Zahid et al., 2022; Amin et al., 2025). Through modulation of cell division, elongation, flowering, fruit set, and stress responses, PGRs have become key tools in modern vegetable production systems. In vegetables, PGRs are used to improve seedling vigor, flowering, fruit set, retention, and final yield, and to alleviate abiotic stresses like drought, salinity, and temperature extremes (Wakchaure et al., 2020; Zahid et al., 2022; Verma et al., 2024). In eggplant, foliar or floral applications of auxin-like compounds (e.g., NAA, 4-CPA, cloxyfonac), gibberellins, and other regulators can significantly increase fruit set, number of fruits per plant, and marketable yield, sometimes without changing cultural practices

(Widiwurjani et al., 2021; Afrin et al., 2024). Under water-scarce conditions, PGRs such as salicylic acid, thiourea, and potassium nitrate help maintain canopy function and fruit quality, supporting yield stability (Wakchaure et al., 2020).

Multiple studies show that appropriate PGR type, concentration, and timing can enhance eggplant yield components, including plant height, leaf area, flower number, fruit number, and individual fruit weight (Wakchaure et al., 2020; Afrin et al., 2024). Yet responses are often genotype- and environment-specific, and sub-optimal doses or combinations may fail to improve final yield due to increased fruit drop or sink regulation by the plant (Alicja et al., 2019). Fruit uniformity is closely linked to processes of flower biology, fruit set, and early fruit development, all of which are hormonally regulated (Bons and Kaur, 2019; Zahid et al., 2022). Differences among flower types (e.g., long vs. short styles) in pollen tube growth, nutrient status, and endogenous hormone balance can determine which flowers set fruit and how fruits develop in size and shape. Transcriptomic analyses further highlight phytohormone-related genes as central regulators of early fruit growth and shape variation (Shi et al., 2023). However, the specific ways exogenous PGRs influence these developmental and physiological mechanisms to improve uniform fruit size and shape in eggplant remain insufficiently characterized.

This study focuses on two central questions: first, whether plant growth regulators can enhance eggplant yield; and second, their roles and underlying mechanisms in improving fruit uniformity. Although field studies on the yield-promoting effects of plant growth regulators in eggplant are relatively abundant, research that treats uniformity as the primary evaluation criterion remains limited. Relevant evidence often needs to be inferred through an integrated assessment of fruit shape formation, floral variation, maturity synchrony, and market quality traits. Accordingly, this study combines evidence from field trial literature with relevant physiological mechanisms to provide a more systematic interpretation of the practical effects of plant growth regulators.

2 Types of Plant Growth Regulators Commonly Used in Eggplant Production

2.1 Auxin regulators and their roles

In eggplant production, the most widely used and common plant growth regulators are still auxin-based compounds, especially IAA, NAA, and 2,4-D. The most direct function of these regulators is to increase the probability of fruit set and, to some extent, reduce flower and fruit drop when pollination is unstable, low-temperature stress occurs, or floral organs develop poorly. Chen et al. (2022) showed that the main purpose of spraying 2,4-D at the flower bud stage in eggplant is usually to reduce floral abscission and promote fruit set. At the molecular level, the SmARF family in eggplant responds significantly to 2,4-D treatment, indicating that the role of exogenous auxin is not simply to “promote fruiting”, but rather to regulate and reshape a whole set of developmental signaling pathways.

NAA has received considerable attention in production practice, partly because of its fruit-setting effect and partly because of its ability to improve fruit shape. Field trial results show that the commonly effective and relatively stable concentration of NAA is usually around 40 ppm. Although the exact value may vary somewhat among cultivars and seasonal conditions, the overall direction of its effect remains consistent. NAA treatment usually increases the effective fruiting rate of long-styled and medium-styled flowers, while also improving leaf photosynthetic capacity and PSII efficiency, which is ultimately reflected in increased fruit number and yield (Moniruzzaman et al., 2014). Amin et al. (2025) tested 40, 50, 60, and 70 ppm NAA together with a control, and the results indicated that 40 ppm was the best treatment: plant height reached 73.73 cm, branch number 9.20, leaf number 97, single-fruit weight 186.67 g, fruit number per plant 10.11, yield per plant 1.31 kg, and estimated yield 41.9 t/ha. This treatment was applied at the 50% flowering stage and again 20 days later. These findings indicate that exogenous auxin regulators can indeed improve fruit set and yield, but their effectiveness depends on an appropriate flowering-stage window and a reasonable concentration; otherwise, excessive hormone application may easily lead to malformed fruits or fruit drop at later stages.

2.2 Gibberellins and cytokinins

Gibberellins, especially GA_3, function in eggplant production more like regulators with an "amplifying effect", as their action is often expressed through simultaneous increases in flower number, fruit number, and individual fruit size. Field trial results showed that treatment with GA_3 at 50 ppm increased the number of fruits per plant to 18.56, compared with 11.34 in the control. Yield per plant increased from 1.38 kg to 1.58 kg, representing an increase of about 14.5%, while the increase in fruit number reached 63.7%. These results indicate that the role of GA_3 in eggplant is not limited to promoting fruit enlargement, but also has a significant effect on the fruit-bearing structure of the plant (Kropi, 2018). GA_3 at 75 ppm is also frequently included in optimal treatment combinations, as it can not only advance the time to 50% flowering, but also further increase fruit number per plant and total yield (Pradeepkumar et al., 2020).

Compared with auxins and GA_3, there is relatively less direct field evidence for cytokinin application in eggplant, but its role in regulating early cell division and buffering stress has become fairly clear. Studies have shown that 6-BA treatment can alleviate the decline in chlorophyll content, reactive oxygen species accumulation, and membrane lipid peroxidation caused by low-temperature stress, while increasing the activities of antioxidant enzymes such as SOD, POD, CAT, APX, and GR. In other words, cytokinins may not show as direct an effect on yield improvement as GA_3, but they play a strong foundational role in seedling uniformity, maintenance of plant vigor, and the eventual formation of uniform fruit set. Further molecular evidence shows that the SmRR family in eggplant is closely associated with cytokinin signal transduction, and some of these genes also respond sensitively to IAA and stress conditions. This suggests that cytokinins do not act independently, but instead participate together with auxins in regulating the developmental rhythm of the plant (Chen et al., 2016).

2.3 Other types of regulators

The role of ethylene and its inhibitors in eggplant cultivation is more closely associated with two aspects: "preventing abscission" and "delaying senescence". The former mainly occurs before fruit formation, as ethylene generally exerts a certain inhibitory effect on fruit set; the latter is mainly expressed during the postharvest stage, when ethylene accelerates fruit senescence and softening. Sharif et al. (2022) reported that the ethylene inhibitor 1-MCP can promote parthenocarpy in some fruit vegetables. In postharvest treatment of eggplant, application of 1-MCP at 5–10 μL/L can significantly delay fruit softening, inhibit the activity of cell wall hydrolytic enzymes, and extend shelf life. These findings suggest that although ethylene inhibitors are not the main regulatory tools for increasing yield in the field, they are of great value in maintaining marketable uniformity and extending the marketing period.

New regulators in the brassinosteroid group are better understood from the perspective of yield stability rather than yield maximization. Studies have shown that under low-temperature stress or during recovery from chilling injury, treatment with 0.1 μM 24-epibrassinolide can reduce the accumulation of MDA, H_2O_2, and superoxide anions in eggplant seedlings, while increasing the activities of enzymes related to the AsA-GSH cycle. This type of regulator has shown certain potential in promoting early recovery of growth, maintaining leaf photosynthesis, and supporting subsequent uniform fruit enlargement (Wu et al., 2015). However, based on currently available public research evidence in eggplant, the conclusion that brassinosteroids can directly increase yield under field conditions is still less consistent than for GA_3 and NAA. Therefore, a more practical application strategy is to regard them as important supplementary tools for regulating plant growth, stabilizing yield, and maintaining quality during stress-prone seasons.

3 Effects of Plant Growth Regulators on Eggplant Yield

3.1 Regulation of flowering and fruit set

The starting point of eggplant yield formation lies in flowering, and many production problems also first emerge during the flowering stage. A high proportion of heterostylous flowers, together with factors such as low temperature, weak light, and fluctuations in water availability, may frequently result in the phenomenon of "flowering without fruit set" (Figure 1). A study on 13 eggplant genotypes showed that the proportion of long-styled and medium-styled flowers, which possess normal fruit-setting ability, ranged from 43.60% to 75.62%, whereas the proportion of short-styled flowers ranged from 20.47% to 45.51%, and these short-styled flowers essentially lacked fruit-setting ability (Khaleghi et al., 2021). This indicates that eggplant itself exhibits clear differences in floral organ type, which is also an important reason why exogenous plant growth regulator treatments applied during flowering often produce obvious effects. NAA and related treatments can improve floral characteristics and promote initial fruit set; in essence, they increase the fertilization success rate of flowers with fruiting potential.

From the perspective of flowering progress, the regulatory effect of GA_3 is usually more direct. Experimental results showed that treatment with GA_3 at 75 ppm advanced the time to 50% flowering to 51.62 days, compared with 58.87 days in the control, representing an advancement of 7.25 days or about 12.3% (Dewangan and Jangre, 2024). In the same experiment, this treatment produced 4.01 flowers per cluster, indicating that GA_3 can not only accelerate flowering but also help improve flowering quality. This change is of considerable practical significance, because once flowering becomes more synchronized, the subsequent fruit-setting process and harvest period also tend to become more concentrated, thereby creating favorable conditions for yield formation and field management.

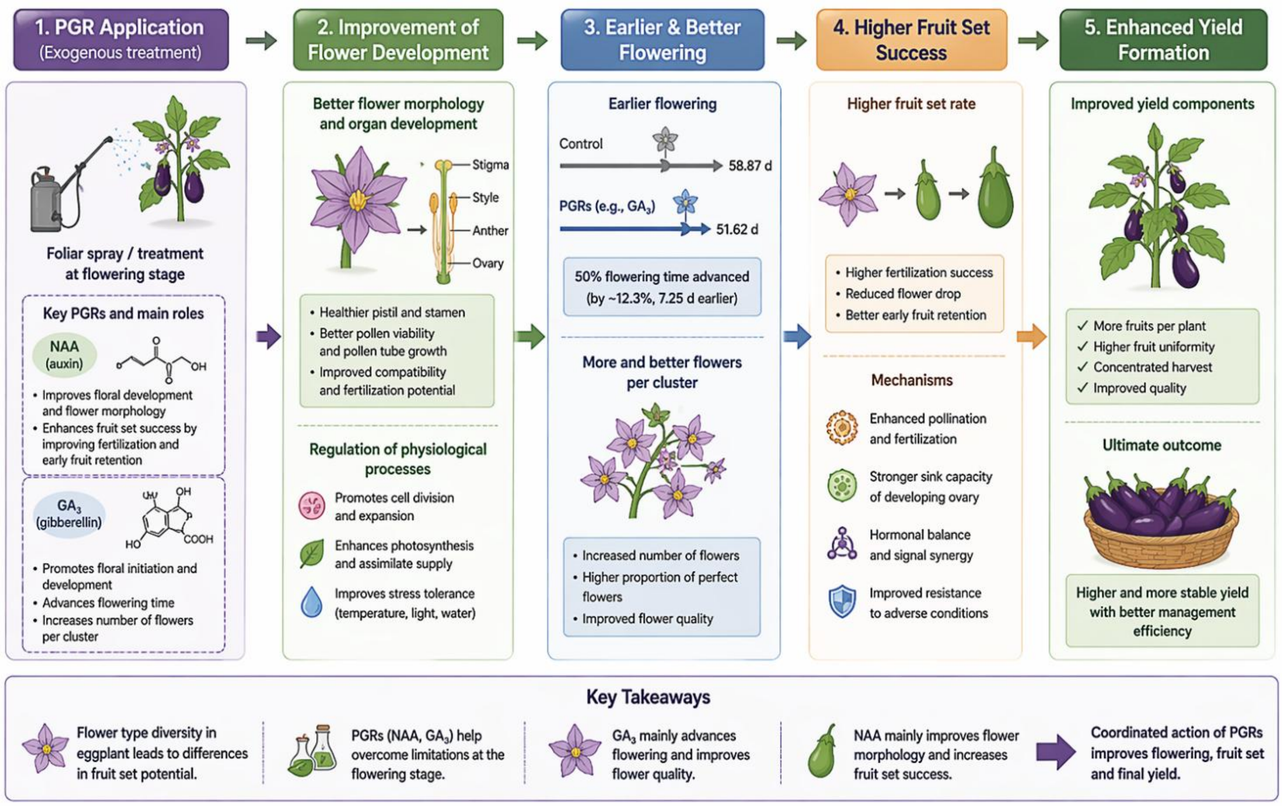

Figure 1 Mechanism of plant growth regulators regulating flowering and fruit set in eggplant

Image caption: This figure illustrates how plant growth regulators regulate flowering and fruit set in eggplant. NAA mainly improves floral development and fruit-setting ability, whereas GA_3 promotes earlier flowering and increases flowers per cluster, jointly enhancing fruit set and yield formation

3.2 Effects on fruit growth and dry matter accumulation

Once fruit set has been completed, subsequent yield formation mainly depends on two key processes: whether cell division is sufficient and whether cell expansion proceeds smoothly. Comparatively speaking, GA_3 tends to play a stronger role in promoting cell elongation and fruit enlargement, whereas auxin regulators often participate in both the cell division and cell expansion stages. Studies have shown that exogenous auxin promotes fruit length increase mainly through the coordinated action of longitudinal cell division and cell expansion, while also enhancing the activity of pathways related to GA biosynthesis and cell wall biosynthesis (Zhao et al., 2025). Through combined morphological and transcriptomic analyses of long-fruited and round-fruited eggplant types, Shi et al. (2023) found that clear fruit-shape differences had already appeared before flowering, indicating that the initiation of fruit differentiation occurs earlier than traditionally assumed. By the sixth day after flowering, the fruits had entered a stage of rapid enlargement. Transcriptomic data further showed that many plant hormone-related genes were already upregulated on the day of flowering, among which SmARF1 maintained consistently high expression, suggesting that auxin signaling plays a crucial role in the early initiation of fruit development. The study also identified multiple differentially expressed genes (DEGs) related to the SUN, YABBY, and OVATE families, among which SmOVATE5 showed a negative regulatory effect, meaning that it suppressed fruit growth. These results clearly indicate that the regulatory window for fruit development has already opened before flowering and during the early flowering stage, and that the timing of regulation is relatively early.

Field data correspond well with the physiological processes described above. Treatment with GA_3 at 50 ppm not only increased the number of fruits per plant, but also raised total dry matter accumulation to 802.40 g per plant, compared with 702.90 g per plant in the control. Results from combination treatments further showed that NAA 40 ppm + GA_3 50 ppm increased single-fruit weight to 180.48 g, while yield per plant reached 2.91 kg (Kropi, 2018). This finding points to a key issue: if only fruit number increases without a simultaneous promotion of fruit enlargement, there is a risk of producing “too many small fruits with only limited improvement in total yield.” By contrast, when NAA and GA_3 are applied together, both fruit number and single-fruit weight can be increased, thereby more effectively enhancing final yield.

3.3 Effects on yield components

In terms of yield components, the number of fruits per plant and single-fruit weight are the two core factors determining eggplant yield level. Because different studies vary considerably in cultivar type, cultivation conditions, and ecological environment, the absolute values obtained in different experiments are not suitable for simple horizontal comparison. However, the general pattern of change is relatively consistent. Research has shown that treatment with GA_3 at 50 ppm increased fruit number per plant from 11.34 to 18.56, while yield per plant rose from 1.38 kg to 1.58 kg (Kropi, 2018). Another study compared the effects of 25, 50, and 75 ppm GA_3 with several micronutrient treatments, and the results indicated that, under those experimental conditions, GA_3 at 25 ppm produced the best improvement in yield traits, especially in fruit number per plant, single-fruit weight, and yield per plant, all of which were superior to the control. This finding highlights an important fact: GA_3 does indeed have the capacity to improve eggplant yield, but its optimum concentration is not fixed; rather, it is jointly influenced by varietal characteristics and ecological conditions. In other words, 75 ppm may perform best in some experiments, whereas under other conditions 25 ppm may produce better results. This indicates that the yield-enhancing effect of GA_3 is objectively real, but its optimal dosage is clearly context-dependent (Bhattarai et al., 2021).

Evaluation of yield stability must also be considered under stress years or unfavorable environmental conditions. Field studies combining water-deficit stress with plant growth regulator treatments provide particularly representative evidence. As irrigation volume gradually decreased from the recommended level, marketable fruit yield rapidly declined to 86%, 74%, 50%, 30%, 12%, and 8% of the control level. However, after the application of regulators such as salicylic acid (SA), potassium nitrate, and thiourea, yield still increased further by 7.3% to 22.7%, while water productivity improved to 5.50–6.77 kg/m^3, compared with only 5.16 kg/m^3 in treatments without regulators (Wakchaure et al., 2020). These results show that the more practical value of plant growth regulators in eggplant production lies not only in further increasing yield under high-yield conditions, but more importantly in reducing the extent of yield loss under stress or difficult seasons, thereby enhancing the stability of yield formation.

4 Effects of Plant Growth Regulators on Fruit Uniformity

4.1 Regulation of fruit shape and size uniformity

In many cases, poor market appearance quality in eggplant is not caused by low average yield, but rather by excessive variation in fruit length, thickness, and curvature. Fruit shape uniformity is closely associated with hormonal balance within the plant. The study by Zhao et al. (2025) provides a relatively clear explanation of this process: exogenous auxin can regulate fruit shape-related genes such as *SmOVATE*, *SmSUN*, and *IQD*, and together with GA-related and cell wall biosynthesis pathways, promote longitudinal cell division and elongation. This indicates that whether a fruit is slender or straight is not determined solely by the genetic background of the cultivar; exogenous regulators may also amplify or reduce such variation. When regulation is appropriate, the distribution of fruit length tends to become more concentrated, whereas excessive regulation may induce excessive elongation or malformed fruits.

From the perspective of practical production, both NAA and GA_3 can improve fruit shape, but their regulatory emphasis differs. NAA tends to stabilize early fruit set and young fruit development, whereas GA_3 more clearly promotes fruit enlargement and longitudinal elongation. Patel et al. (2022) showed that under combined NAA and GA_3 treatment, fruit length, fruit diameter, and single-fruit weight all increased, and this improvement occurred synchronously rather than merely as simple fruit elongation accompanied by insufficient lateral growth. This phenomenon is highly meaningful in commercial production, because fruit grading is most negatively affected by unevenness such as “some fruits being too long while others are too thin”, whereas combined regulation is usually more effective than a single regulator in narrowing the range of fruit-shape variation. It should be noted that field studies directly evaluating eggplant uniformity using the coefficient of variation of fruit shape are still relatively limited. Therefore, the judgment of “uniformity” here is mainly inferred from the simultaneous improvement of fruit shape-related traits.

4.2 Regulation of fruit developmental synchrony

Another important aspect of fruit uniformity is whether the developmental rhythm remains relatively synchronized. If the flowering time within the same batch differs substantially, the subsequent fruit-setting and ripening processes usually also become clearly dispersed. The role of GA_3 in promoting earlier flowering and increasing the number of flowers per cluster already reflects a certain “synchronizing” effect. Combined with studies on heterostylous flowers in eggplant, it can be seen that when the proportion of long-styled and medium-styled flowers increases, early effective fruit set tends to become more concentrated, and the subsequent fruit developmental window also becomes more uniform (Dewangan and Jangre, 2024). This has strong practical value in production: for manual harvesting, it reduces the frequency of repeated picking rounds; for protected cultivation, it also facilitates the unified scheduling of water and fertilizer management as well as pest and disease control measures.

Uniformity of ripening is also closely related to whether “lagging fruits” appear under stress conditions. Once adverse environments such as drought, salinity stress, or low temperature cause some fruits to suspend development, clear stratification often emerges within the whole fruit batch. Although regulators such as SA, 6-BA, and EBR may not show yield-promoting effects as directly as GA_3, they can maintain chlorophyll content, relative water content, membrane stability, and antioxidant capacity, thereby reducing the risk of growth stagnation during critical developmental stages (Mady et al., 2023). Under such conditions, fruit development is more likely to remain synchronized, and the ripening period also tends to become more concentrated. Although this effect may not be highly dramatic, it has considerable practical value in improving fruit uniformity.

4.3 Quality traits related to marketability

From the perspective of market evaluation, whether eggplant fruits are “uniform” is usually reflected in four major indicators: fruit size, color, firmness, and surface defects. Existing studies on marketability consistency have largely focused on these aspects. In the field trial conducted by Wakchaure et al. (2020), marketable fruit quality was defined in terms of average fruit weight, fruit diameter, sphericity, and firmness, and the study clearly showed that these indicators were jointly affected by irrigation level and plant growth regulator treatment. Research on the genetic basis of appearance traits has also shown that peel anthocyanin composition, surface texture, and fruit surface appearance directly affect the commercial value of eggplant. This suggests that so-called "uniformity" is not an abstract concept, but one that is ultimately reflected in grading standards and market price.

Among these traits, peel color is especially critical under protected winter production conditions. Weak light environments easily lead to problems such as uneven pigmentation, whitening, and blotchy coloration. Luo et al. (2023) reported that low light reduces the visual quality and commercial value of eggplant peel, whereas materials that can maintain good coloration under low-light conditions are particularly valuable for commercial production. Further studies have shown that peel color at different developmental stages is jointly determined by a series of metabolites and regulatory genes. In other words, if plant growth regulators can stabilize the overall physiological status of the plant, or maintain anthocyanin accumulation during the later stages of fruit development in combination with cultivar characteristics, then improved uniformity may ultimately be expressed as more consistent fruit coloration and more stable appearance quality.

5 Physiological and Molecular Mechanisms

5.1 Hormonal signaling pathways

Plant growth regulators (PGRs) influence eggplant yield and uniformity by reshaping hormonal networks, carbon allocation, and stress responses that control fruit set, growth, and stability. Auxin and gibberellin (GA) act as primary drivers of fruit initiation, cell division and expansion, often sufficient to induce parthenocarpy when applied exogenously (Fenn and Giovannoni, 2020; He and Yamamuro, 2022; Su et al., 2025). Crosstalk occurs through direct interaction between auxin-responsive ARF/IAA proteins and GA repressor DELLA proteins, which co-regulate genes for hormone metabolism and fruit growth, integrating auxin and GA signals into a unified control of fruit set and early enlargement (Hu et al., 2018; He and Yamamuro, 2022). Cytokinin cooperates with auxin and GA to enhance parthenocarpic fruit set in cucumber, with high cytokinin and GA but low abscisic acid (ABA) characterizing highly parthenocarpic genotypes (Su et al., 2021; 2025; Zhao et al., 2025).

These hormones coordinate transcriptional programs: auxin–GA complexes modulate feedback genes in their own pathways and activate fruit growth-related genes, while cytokinin-responsive type-B response regulators and auxin-regulated ARFs mediate broad transcriptional reprogramming during fruit development (Fenn and Giovannoni, 2020). Shifts in ABA and ethylene further remodel gene expression at maturation and under stress, influencing fruit size and development patterns (Fenn and Giovannoni, 2020; Waadt et al., 2022; Thilakarathne et al., 2025).

5.2 Metabolic and cellular processes

PGRs indirectly govern carbohydrate allocation by altering sink strength in developing fruits. Sugar transporters and sugar–hormone integration ensure that sink organs such as fruits receive sufficient carbohydrates, with sugars acting as both substrates and signals that interact with auxin and cytokinin pathways (Wingler and Henriques, 2022; Guo et al., 2023). Under carbon restriction, marked declines in cytokinins and downregulation of cytokinin biosynthesis genes coincide with reduced expansin expression and fruit weight, showing that cytokinins drive not only cell division but also cell wall loosening and expansion (Nardozza et al., 2020).

At the cellular level, auxin and GA jointly promote cell division and subsequent expansion in early fruit development across multiple species, while cytokinins modulate both proliferation and elongation through expansin-linked cell wall relaxation (He and Yamamuro, 2022). Sugar-auxin crosstalk further integrates metabolic status with cell cycle activity, chromatin state and auxin-regulated gene expression, ensuring that cell division and differentiation proceed only when carbohydrate supply is adequate (Sabagh et al., 2022).

5.3 Stress responses and hormonal regulation

Abiotic stresses such as drought, salinity, heat and flooding disrupt endogenous hormone balances, compromising reproductive development and yield stability (Waadt et al., 2022; Baral et al., 2025). PGRs—endogenous or applied—mitigate these effects by reconfiguring hormonal networks: ABA, salicylic acid, ethylene and jasmonates primarily activate defense and osmotic adjustment, while auxin, GA and cytokinins maintain growth, with extensive crosstalk between stress and growth pathways (Sabagh et al., 2022; Baral et al., 2025).

GA-inhibiting triazoles such as paclobutrazol alter gibberellin, ABA and cytokinin levels, reducing excessive vegetative growth, enhancing carbohydrate accumulation, improving water status and strengthening tolerance to abiotic stress while supporting fruit number and quality (Desta and Amare, 2021; Sabagh et al., 2021). Under low sugar availability or environmental stress, sugar signaling promotes ABA and ethylene accumulation and disrupts auxin transport, driving fruit abscission; once sugar status improves, rising cytokinin and GA levels restore cell division and expansion and stabilize fruit set (Waadt et al., 2022; Zhao et al., 2025). Thus, PGR-mediated adjustment of hormonal networks links stress physiology directly to yield stability and fruit uniformity.

6 Application Strategies of PGRs in Eggplant Production

6.1 Application methods and timing

Plant growth regulators can substantially improve eggplant yield, stress tolerance, and fruit quality, but their benefits depend strongly on application method, timing, and dose. Foliar spraying is the most common method in eggplant, enabling rapid absorption and relatively precise timing around key stages such as vegetative growth, flowering, and early fruit set (Figure 2). Foliar application of α-tocopherol, ZnO nanoparticles, salicylic acid, potassium nitrate, thiourea, and biostimulants (garlic extract, vermicompost tea, yeast extract) enhanced growth, water status, antioxidant activity, and yield under both optimal and drought conditions (Semida et al., 2021; Akram et al., 2023). Foliar PGRs are usually applied with surfactants to improve cuticular penetration and uniform coverage (Akram et al., 2023; Dick and VanderWeide, 2025).

Root-zone or substrate applications are preferred for some systemic regulators such as paclobutrazol, which is more effective when applied to the growth medium than as a spray because of longer contact and uptake time (Desta and Amare, 2021). Seed priming with PGRs (e.g., α-tocopherol, guvermectin) can enhance early vigor and later yield response, representing a complementary strategy to foliar use (Liu et al., 2022; Akram et al., 2023).

Optimal timing is crop- and regulator-specific. In fruit crops, foliar PGRs applied at full bloom or shortly after flowering markedly influence fruit set, size, and quality (Aryal and Alférez, 2025; Baldissera et al., 2025). In eggplant, applications at vegetative and pre- or post-transplant stages, as well as around flowering and early fruit set, were most effective for stimulating canopy growth, maintaining water status, and improving yield and fruit traits under water stress (Ali et al., 2019; Wakchaure et al., 2020). Repeated applications may increase responses but excessive frequency can cause growth inhibition or oxidative damage.

6.2 Dosage optimization and combination use

PGRs exhibit clear dose–response relationships: low to moderate concentrations often stimulate growth and yield, whereas high doses can induce phytotoxicity or yield decline (Ali et al., 2019; Semida et al., 2021; Akram et al., 2023). In eggplant, moderate foliar levels of α-tocopherol or ZnO nanoparticles maximized growth and fruit yield under drought, while higher doses or over-frequent botanical sprays increased lipid peroxidation and reduced growth (Akram et al., 2023). Similar patterns are reported for auxins, gibberellins, and cytokinins in cucurbits and tree fruits, where recommended ppm ranges are critical to avoid negative effects on fruit quality or return bloom (Sabir et al., 2021; Baldissera et al., 2025).

Combination treatments can produce synergistic effects by targeting complementary hormonal pathways. In cucumber, combined auxin and gibberellin improved vegetative growth and fruit yield more than either alone (Gosai et al., 2020). In apple, combinations of cytokinin (BA) and auxin (NAA) increased yield and the proportion of large fruits beyond single applications (Baldissera et al., 2025). In eggplant under deficit irrigation, mixtures of salicylic acid, potassium nitrate, thiourea, or commercial biostimulants improved canopy traits, water productivity, and fruit quality compared with untreated controls, with some regulators more effective under specific stress intensities (Wakchaure et al., 2020). These findings support careful factorial trials in eggplant to identify synergistic PGR combinations and avoid antagonistic or redundant effects.

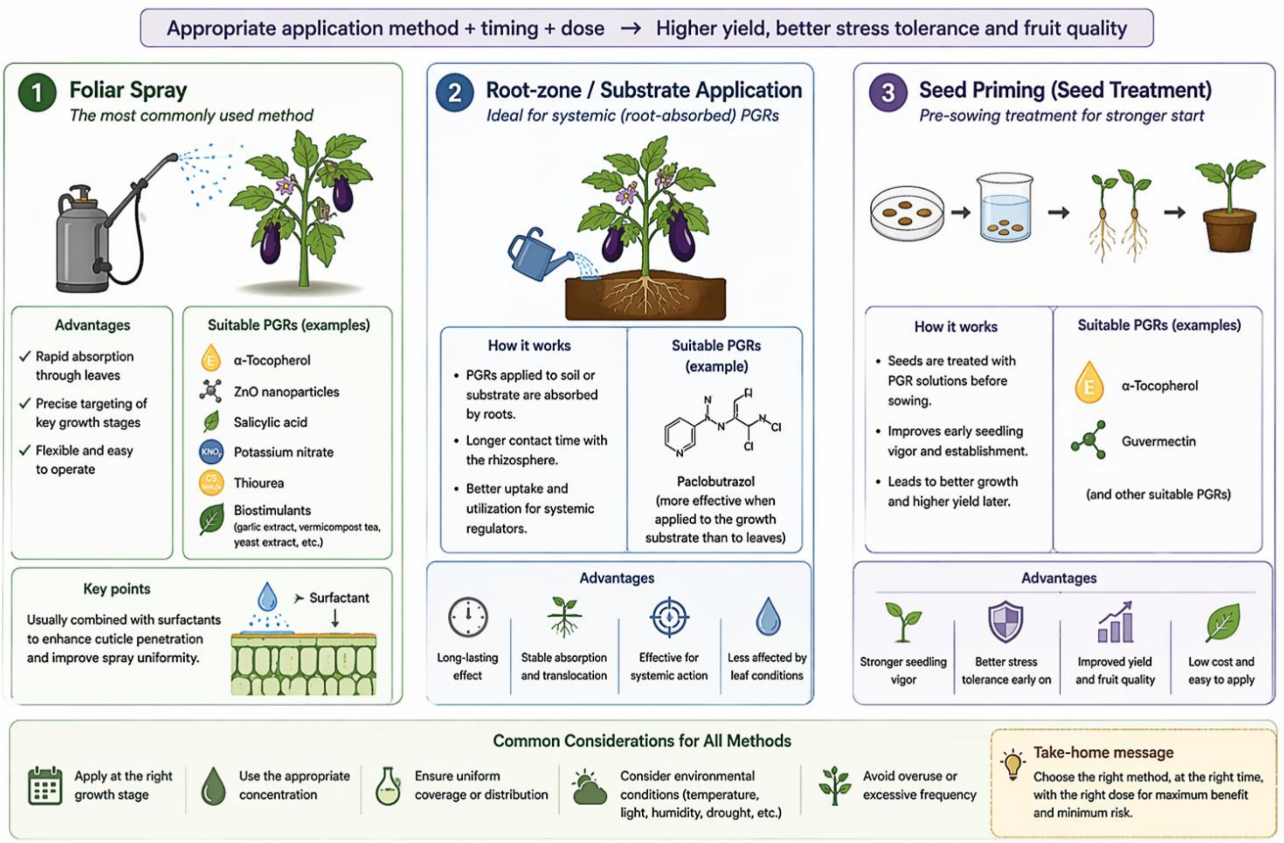

Figure 2 Main application methods of plant growth regulators in eggplant production

Image caption: This figure shows the three main application methods of plant growth regulators in eggplant production, including foliar spray, root-zone or substrate application, and seed priming, and compares their targets, functional features, and practical advantages

6.3 Safety and environmental considerations

Despite agronomic benefits, PGR use raises concerns about residues in edible tissues and broader environmental impacts. Surveys in vegetables have detected multiple endogenous-type PGR residues (auxins, gibberellins, cytokinins) in a high proportion of market samples, with gibberellins sometimes exceeding maximum residue limits set by European, US, and Japanese regulations (Le et al., 2020; Zhou et al., 2025). Reviews highlight mammalian toxicities (hepatic, renal, reproductive, carcinogenic) associated with specific synthetic PGRs, emphasizing the importance of dose-response analysis and rigorous risk assessment (Zhou et al., 2025).

In soils, PGRs undergo adsorption, desorption, hydrolysis, photolysis, and microbial degradation, and their persistence and mobility determine risks to non-target organisms and groundwater (Chen et al., 2022). In some production systems, misuse and overuse have led to declining product quality and dual contamination of crops and cultivation environments, prompting calls for stricter registration, residue limits, and monitoring (Zhang et al., 2020; Zhou et al., 2025).

Sustainable PGR use in eggplant should therefore prioritize: adherence to registered products and label doses; minimal effective application frequency; preference for lower-risk or biogenic regulators and biostimulants where possible; and integration with cultural and irrigation management to reduce dependence on chemical inputs (Akram et al., 2023; Liu et al., 2024). Development of high-throughput residue testing and clearer maximum residue limits can support safer adoption while maintaining the yield and uniformity benefits sought in commercial eggplant production (Le et al., 2020; Zhou et al., 2025).

7 Concluding Remarks

A synthesis of the available studies shows that plant growth regulators can indeed improve eggplant yield and, to some extent, enhance fruit uniformity, although different types of regulators differ in their primary functions. For example, GA_3 is more effective at improving flowering quality, increasing fruit number, and promoting fruit enlargement; NAA is more beneficial for stabilizing fruit set, reducing flower and fruit drop, and supporting fruit shape formation; whereas 6-BA, SA, and EBR are better suited to maintaining growth continuity under stress conditions and reducing developmental differences among fruit batches. For commercial production, the most practical benefits lie in a more stable fruiting process, more uniform fruit shape, and a more concentrated ripening period. Mechanistically, these effects are not independent of one another. Auxins, gibberellins, and cytokinins collectively participate in fruit initiation, cell division, and enlargement, while central carbon metabolism, cell wall synthesis, and stress-related antioxidant systems determine whether these hormonal signals can ultimately be translated into successful fruit elongation and stable fruit development. Precisely because this regulatory network is complex, the same regulator often shows considerable variation in performance across different cultivars, seasons, and protected cultivation conditions.

At present, the most prominent issue is whether the effects of plant growth regulators can be reproduced consistently. On the one hand, existing field trials on plant growth regulators in eggplant are still strongly region-specific, with substantial differences in cultivar type, seasonal conditions, and cultivation management background, making it difficult to apply optimal dosages and treatment timing directly across production systems. On the other hand, studies on fruit uniformity are clearly fewer than those on yield. Many papers report only fruit number, single-fruit weight, and total yield, while giving much less attention to indicators such as coefficients of variation, marketable grading proportion, and ripening synchrony index. As a result, assessments of consistency often remain at the level of indirect inference. At the molecular level, although a number of key regulatory factors have been identified, including *SmARF*, *SmRR*, *SmOVATE5*, and *SmMYB113*, there are still relatively few studies that fully connect the chain from “exogenous regulator–signal transduction-fruit shape uniformity-commercial grading.” In particular, direct field evidence for the roles of cytokinins, ethylene inhibitors, and brassinosteroids in regulating eggplant uniformity remains limited, indicating that this field still has substantial room for expansion.

Future research may be advanced from three main directions. First, greater emphasis should be placed on the study of hormonal interactions, rather than continuing to focus primarily on the effects of single compounds. Existing studies have already shown certain advantages of combined NAA and GA_3 treatment, and future work could incorporate auxins, gibberellins, cytokinins, and brassinosteroids into a unified temporal framework for systematic investigation. Second, the evaluation system for fruit uniformity should be further improved. Instead of judging treatment effects only by mean values, comprehensive assessment should include indices such as fruit length variation, dispersion of single-fruit weight, ripening concentration, and commercial grading rate. Third, the application of plant growth regulators should be increasingly integrated with precision regulation and smart agriculture technologies. As fruit recognition and counting technologies in greenhouse production continue to mature, it should become entirely feasible to further combine flowering-stage recognition, environmental monitoring, and site-specific spraying technologies, thereby shifting regulator application from traditional experience-based operation to precise intervention based on key developmental stages.

Acknowledgments

The authors would like to express their sincere gratitude to Ms. Zhang for her assistance in organizing the literature materials. The authors also extend special thanks to the two anonymous peer reviewers for their comprehensive evaluation of the 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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