

Indian Pomegranate Exports: Production, Residue Compliance, Quality and Market Constraints

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Abstract— India is a major producer of pomegranate, yet only a small proportion of its production enters international markets, indicating a persistent gap between production capacity and export performance. This review synthesizes evidence on the production, fruit quality, pesticide use, residue, post-harvest, phytosanitary, and market factors that shape the exportability of Indian pomegranate. India produced about 3.16 million tonnes of pomegranate in 2022-23, while only around 2.5% was exported, despite substantial growth in export value over the past decade. The review shows that export constraints begin at the farm level, where pest and disease pressure and frequent pesticide application can affect fruit quality and compliance with residue requirements, while inadequate farm-level documentation can limit traceability. Residue studies from India demonstrate considerable variation among regions and sampling periods, with both compliant samples and samples exceeding applicable MRLs reported. Importantly, regulatory compliance with MRLs and dietary-health risk are distinct considerations and should not be interpreted interchangeably. Beyond production, inadequate pre-cooling, grading, packhouse capacity, integrated cold chains and processing infrastructure can reduce the quality achieved in the orchard, particularly for highly perishable arils. Market access is further influenced by destination-specific sanitary and phytosanitary requirements, certification, traceability, labelling, tariffs and other non-tariff measures. Exports remain concentrated in regional markets, whereas substantially higher price realizations have been reported for selected high-value destinations. The evidence indicates that increasing exports therefore requires a coordinated value-chain approach rather than greater production alone. Priority areas include export-oriented crop protection, residue-compliant production, farm-level traceability, cluster-based post-harvest infrastructure, value addition, market diversification and stronger alignment between production systems and destination-market requirements.

Keywords— Export competitiveness; Pesticide residues; Maximum residue limits; Traceability; Post-harvest management.

I. INTRODUCTION

Pomegranate (*Punica granatum* L.) is an important fruit crop of arid and semi-arid regions and has become an economically important horticultural commodity in India. The crop is valued for its nutritional properties, attractive fruit characteristics, and growing demand in domestic and international markets. India has a diverse range of pomegranate cultivars, although only a limited number are cultivated commercially. Among them, Bhagwa has emerged as an important commercial and export variety

because of its attractive rind and aril colour, sweetness, good keeping quality, and high yield (Prasad et al., 2013; Saroj and Sharma, 2017). Pomegranate cultivation is concentrated mainly in Maharashtra, Karnataka, Gujarat, and Andhra Pradesh, with Maharashtra being the leading producing state. India also has an important advantage in terms of fruit availability, as pomegranate can be produced throughout the year, while several competing countries have more restricted production seasons (Kahramanoglu, 2019).

Despite this production strength, only a small proportion of Indian pomegranate reaches international markets. In TE 2022-23, India produced about 3.16 million metric tonnes of pomegranate, while only about 2.5 per cent of the production was exported (Rao et al., 2026). Indian pomegranate exports have increased substantially over the years, with export value rising from USD 15.57 million in 2010-11 to USD 69.08 million in 2023-24 (Rao et al., 2026). However, a large share of exports continues to be directed towards a limited number of markets, particularly the United Arab Emirates, Bangladesh and Nepal (Rao et al., 2026). This difference between the scale of production and the quantity entering international trade raises an important question: why has India not been able to convert its large production base into a much larger and more diversified export presence?

Export performance in fresh fruit depends on more than production volume. Fruit intended for international markets must meet specific requirements related to size, colour, appearance, surface quality, variety, shelf life, and absence of pests and diseases. In pomegranate, these characteristics can be influenced by cultivar, agro-climatic conditions, nutrient and water management, pest and disease pressure, and harvesting practices. A diverse insect and non-insect pest complex has been reported on pomegranate, and damage caused by these pests can reduce yield, fruit quality, and marketability (Kulkarni et al., 2007; Balikai et al., 2011; Balikai et al., 2022). Diseases such as bacterial blight, wilt, anthracnose, and fruit rots also affect production and fruit quality, with bacterial blight being one of the major constraints in Indian pomegranate production (Doddaraju et al., 2019; Sharma et al., 2021). Recent assessments of the export sector have also identified fruit size, colour variation, bacterial blight, and varietal inconsistency among the factors that can reduce export readiness (Rao et al., 2026).

Crop protection practices are closely related to the quality and safety requirements of export-oriented production. Because pomegranate is affected by a diverse pest and disease complex, chemical pesticides remain an important component of crop protection in commercial orchards. Studies have reported considerable dependence on synthetic pesticides and frequent pesticide applications. In some production systems, spraying has been largely calendar-based rather than based on actual pest incidence (Elango and Sridharan, 2017). In addition, deficiencies in farmer awareness regarding pesticide residues, maximum residue limits (MRLs), pre-harvest intervals (PHIs), recommended dosages, and safe pesticide use have been reported in several agricultural production systems (Anbazhagan et al., 2022; Kumar et al., 2023; Prasad et al., 2023; Vallur et al., 2023). These practices are relevant to export production because decisions regarding pesticide selection, application rate, and timing are made at the farm level, whereas the harvested fruit must satisfy the residue requirements of the destination market.

Pesticide residues have consequently become an important consideration in the export of pomegranate. Residue-monitoring studies conducted in India have detected several insecticides and fungicides in pomegranate fruit, with considerable variation among regions, seasons and sampling sources. An early large-scale study of export-oriented pomegranate from Maharashtra and Karnataka detected residues belonging to several pesticide groups, and a proportion of the samples exceeded European Union MRLs (Kolekar et al., 2011). Subsequent studies have also reported pesticide residues in pomegranate from different parts of India (Kottadiyil et al., 2023; Aralimarad et al., 2024). These findings need to be interpreted carefully because the detection of a residue does not by itself indicate a dietary health risk. However, residues exceeding the MRL applicable to a particular pesticide-commodity combination can create a regulatory and commercial problem, particularly when the produce is intended for export markets (Dureja et al., 2015; Ambrus and Yang, 2016).

The issue becomes more important because residue standards and other regulatory requirements differ among importing countries. Pomegranate intended for export may therefore need to comply with requirements related to pesticide residues, phytosanitary measures, certification, traceability, labelling and food safety. Differences among Indian, Codex, and European Union requirements can influence pesticide selection, spray schedules, and PHI management in export-oriented orchards (Dureja et al., 2015; Ambrus and Yang, 2016; Pasupuleti et al., 2022). Residue studies have also shown that pesticide persistence in pomegranate varies with the pesticide used, dose, environmental conditions, and fruit characteristics, making crop-specific residue and dissipation information important for determining appropriate PHIs and maintaining residue compliance (Hem et al., 2010; Mohapatra and Lekha, 2016; Parmar et al., 2025).

The constraints to export do not end at the farm. Pomegranate is a perishable commodity and requires proper harvesting, grading, packing, storage, and transportation to retain its quality. Inadequate primary grading and collection facilities, limited pre-cooling and cold-storage infrastructure, fragmented cold-chain systems, and insufficient processing facilities can contribute to quality deterioration and post-harvest losses. These limitations are particularly important for minimally processed arils, which require rapid cooling and continuous temperature control. The development of cluster-based facilities, improved packhouses, cold-chain systems, traceability, and processing infrastructure has therefore been identified as important for strengthening the efficiency of the Indian pomegranate export value chain (Gulati et al., 2022). Market access also depends on sanitary and phytosanitary requirements, certification, traceability, labelling and other non-tariff measures. Countries such as those in the European Union and other high-value markets may impose stringent requirements related to pesticide residues, pests and diseases, and product certification. Compliance with these requirements can increase the cost and complexity of exporting fresh fruit, particularly for small and fragmented producers. Thus, export competitiveness depends on the ability to produce fruit that consistently meets the required quality and safety standards and to maintain these standards through the subsequent stages of the supply chain.

The available literature on Indian pomegranate is distributed across different areas, including production, pest and disease management, pesticide use, residue monitoring, food safety, post-harvest handling and international trade. However, these aspects have largely been examined separately. Bringing them together is important for understanding the gap between India's production potential and its export performance. In particular, farm-level crop protection practices, residue compliance, fruit quality, post-harvest handling and market-access requirements are interconnected parts of the same export chain rather than isolated issues.

The present review therefore examines the major factors influencing the export of Indian pomegranate, with particular emphasis on production and fruit-quality constraints, crop-protection practices and pesticide-residue compliance, post-harvest and value-chain limitations, phytosanitary and other market-access requirements, and the opportunities available for expanding India's presence in international markets. The review aims to bring these aspects together to identify the major points at which constraints arise and to discuss how improvements across the production-to-export chain could contribute to more consistent and competitive Indian pomegranate exports.

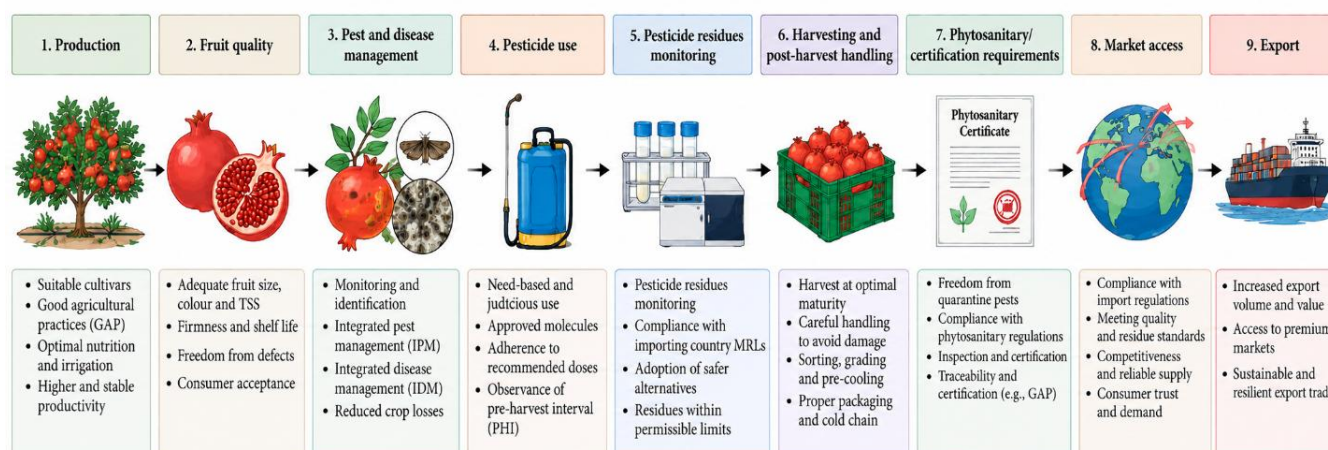


FIGURE 1: Conceptual framework of the major factors influencing the exportability of Indian pomegranate, from production and fruit quality through crop protection, pesticide-residue compliance, post-harvest handling, phytosanitary requirements, market access and export.

II. POMEGRANATE PRODUCTION AND EXPORT POSITION OF INDIA

India is among the major pomegranate-producing countries in the world. The crop is cultivated mainly in Maharashtra, Karnataka, Gujarat, and Andhra Pradesh, with Maharashtra accounting for the largest share of the country's production. The expansion of pomegranate cultivation in India has been associated with an increase in both cultivated area and productivity, particularly following the wider adoption of commercially preferred cultivars such as Bhagwa. The increase in production has also been supported by the suitability of pomegranate to arid and semi-arid agro-climatic conditions and by its relatively high economic returns compared with several other horticultural crops (Prasad et al., 2013; Saroj and Sharma, 2017).

According to Rao et al. (2026), India produced approximately 3.16 million metric tonnes of pomegranate in 2022-23 from about 0.3 million hectares of cultivated area. However, only about 2.5 per cent of the total production entered export markets. More recent production estimates reported by Rao et al. (2026) indicate continued growth in the country's pomegranate production, with approximately 2.9 million metric tonnes produced during 2023-24. Maharashtra remained the leading producing state, accounting for more than half of the country's production, followed by Gujarat, Karnataka, Rajasthan and Andhra Pradesh (Rao et al., 2026). The continued expansion of production indicates that availability of fruit is not, by itself, the major limitation to increasing exports.

Pomegranate also offers India an important seasonal advantage in international trade. Production in Maharashtra and Gujarat extends across the year, while several competing countries have more restricted harvesting periods. This provides an opportunity for India to supply international markets during periods when fruit availability from some other producing countries is relatively low (Kahramanoglu, 2019). The Bhagwa cultivar further strengthens this opportunity because of its attractive rind and aril colour, sweetness, keeping quality, and consumer acceptance. Bhagwa has therefore become the principal cultivar associated with Indian pomegranate exports, while cultivars such as Ganesh, Phule Arakta, Ruby and Mridula contribute to production and are exported to a more limited extent (Prasad et al., 2013; Saroj and Sharma, 2017).

Despite these advantages, the growth in production has not been accompanied by a proportionate increase in exports. Indian pomegranate export value increased from approximately USD 15.57 million in 2010-11 to USD 69.08 million in 2023-24, representing substantial growth over the period (Rao et al., 2026). However, the recent export trend has been less consistent than the earlier period of rapid expansion. The domestic market has remained an important destination for Indian pomegranate, and in some years, better domestic prices have reduced the incentive to send fruit to export markets (Rao et al., 2026). However, in recent years, heavy domestic supply has destabilized the market, and prices have dropped sharply. Thus, the export problem is not simply a question of producing more fruit; it also concerns the ability to consistently produce, handle, and market fruit that satisfies the requirements of international buyers as well as stabilize the domestic market.

Another important feature of India's export profile is the concentration of exports in a relatively small number of destinations. The United Arab Emirates, Bangladesh, and Nepal account for a substantial share of Indian pomegranate exports, while countries such as the Netherlands and Qatar also receive Indian fruit (Rao et al., 2026). This concentration provides established market channels for Indian producers but also indicates limited diversification into some high-value markets. Expanding into such markets requires fruit to meet more demanding requirements related to quality, residue compliance, traceability, phytosanitary measures, certification, and post-harvest handling.

Comparison with other producing countries also needs to be interpreted cautiously because internationally comparable pomegranate-specific trade data are limited. Pomegranates are included under the broader HS 081090 category in international trade statistics, together with several other fruits, making it difficult to obtain accurate country-wise comparisons of pomegranate exports and imports. Country-specific information is therefore often compiled from national statistical agencies and other sectoral sources rather than from a single internationally standardized database (Ergun, 2012).

The production-export gap therefore points to a broader issue in the Indian pomegranate sector. India possesses a substantial production base, a commercially established export cultivar, and a long production season, but these advantages do not automatically translate into access to all international markets. Fruit leaving the orchard must retain the required physical quality, comply with food-safety and residue standards, meet phytosanitary requirements, and remain commercially viable through packing, storage, and transportation. Therefore, the reasons for the limited conversion of production into exportable fruit need to be examined across the entire production and supply chain, not from the perspective of production volume alone.

This production-export gap forms the basis for examining the specific constraints affecting export readiness, beginning with fruit quality and crop protection at the farm level and extending to residue compliance, post-harvest handling, infrastructure and international market-access requirements.

III. PRODUCTION AND FRUIT QUALITY CONSTRAINTS AFFECTING EXPORTABILITY

The ability to export pomegranate depends first on the production of fruit that meets the physical and quality requirements of the target market. Although India has a strong production base and an established export cultivar in Bhagwa, differences in fruit size, colour, appearance, varietal consistency, and overall quality can reduce the proportion of fruit suitable for premium

export markets. Bhagwa is widely preferred because of its attractive rind and aril colour, sweetness, and good keeping quality, and it has gained strong acceptance in domestic as well as international markets (Prasad et al., 2013; Saroj and Sharma, 2017). However, the characteristics of fruit produced under different production conditions are not always uniform, which can affect their acceptance in demanding export markets.

Fruit size is one of the important quality attributes influencing export potential. The available assessment of the Indian pomegranate sector identified relatively small fruit size as a constraint, particularly in markets where larger fruits are preferred. Differences in fruit size can arise from cultivar characteristics as well as orchard management and growing conditions. The issue is particularly relevant for high-value markets where buyers often follow specific size and appearance specifications. Thus, increasing production without achieving the required fruit size may not substantially increase the quantity of fruit that can be marketed as premium export produce (Rao et al., 2026).

Colour and external appearance are also important because pomegranate is commonly marketed as a whole fresh fruit. The attractive rind colour and deep red arils of Bhagwa contribute to its market acceptance (Saroj and Sharma, 2017). However, colour development can be affected by growing conditions, particularly during periods of high temperature. Variation in colour, together with surface blemishes and other external defects, can reduce the market value of fruit even when the internal edible portion remains acceptable. Recent observations from the Indian export sector have identified summer colour variation and surface quality as important considerations for improving export-grade production (Rao et al., 2026).

Varietal consistency is another consideration for export-oriented production. Although Bhagwa has become the principal commercial and export cultivar, several other varieties are grown in different parts of the country. The characteristics of these cultivars differ in terms of fruit size, colour, seed softness, keeping quality, and other market-related traits (Prasad et al., 2013). Such variation can make it difficult to maintain a uniform supply when buyers require consistent fruit characteristics. The availability of suitable planting material and the development or selection of cultivars with desirable export attributes are therefore important for maintaining consistency in quality (Rao et al., 2026).

Pests and diseases add another layer to the quality problem. A diverse insect and non-insect pest complex has been reported on pomegranate, and infestation can affect different plant parts and reduce fruit yield, quality, and marketability (Kulkarni et al., 2007; Balikai et al., 2011; Balikai et al., 2022). Among diseases, bacterial blight caused by *Xanthomonas axonopodis* pv. *punicae* is considered one of the most destructive diseases of pomegranate in India, with severe outbreaks capable of causing substantial yield losses (Doddaraju et al., 2019). Other diseases, including wilt, anthracnose, fruit rots, Alternaria diseases, and Phytophthora-associated diseases, can also affect fruit production and quality (Sharma et al., 2021). Consequently, the production of export-grade fruit requires effective management of both insect pests and diseases throughout the crop season.

The relationship between pest management and export quality is particularly important because cosmetic damage can directly affect the marketability of fresh fruit. Insects that damage the rind or developing fruit may reduce the visual quality required by export markets. At the same time, the need to protect the crop from pests and diseases can increase dependence on pesticides. This creates an additional challenge for export-oriented production because crop protection measures must control the target problem without compromising residue compliance at harvest.

Production conditions can further influence the consistency of fruit quality. Pomegranate is cultivated across a range of agro-climatic regions in India, and differences in climate, orchard management, and cultivar performance contribute to variation in yield and fruit characteristics. Maharashtra remains the major production state, but differences in productivity among producing states indicate that there is further scope for improving production efficiency (Rao et al., 2026). The challenge for export-oriented production is therefore not simply to increase total production, but to improve the proportion of fruit that meets the required specifications of the intended market.

The available evidence suggests that production and quality constraints should be considered together with the requirements of the export market. Fruit that is produced in sufficient quantity but does not meet specifications for size, colour, appearance, disease freedom or consistency may have limited access to premium markets. This makes export-oriented production different from production aimed only at the domestic market. Improving the quantity of fruit suitable for export consequently requires attention to cultivar selection, orchard management, pest and disease management, and the maintenance of consistent quality from the field onwards.

IV. PESTICIDE USE PRACTICES AND THEIR IMPLICATIONS FOR EXPORT READINESS

Pesticide use is an important component of pomegranate production because the crop is affected by a wide range of insect pests and diseases that can reduce fruit yield and market quality. Studies from pomegranate-growing regions have reported the use of chemical insecticides for managing important pests, while the pattern of pesticide use is also influenced by farmers' access to technical information, local production practices, and advisory services (Chauhan and Gupta, 2024; Kambrekar et al., 2015a, 2015b). Thus, the way pesticides are selected and applied at the farm level has implications beyond pest control, particularly when the produce is intended for markets with strict food-safety requirements.

One of the important concerns reported in pomegranate cultivation is the continued use of calendar-based pesticide application rather than applications based on pest incidence. Elango and Sridharan (2017) reported that most pomegranate growers followed predetermined spray intervals, while only a small proportion based pesticide application on actual pest infestation. The same study indicated frequent insecticide applications during the cropping season. Such practices can increase the overall number of pesticide applications even when pest pressure does not justify repeated treatment. Field studies on important pomegranate pests have also demonstrated the continued role of insecticides in crop protection (Kambrekar et al., 2015a, 2015b), highlighting the need to integrate chemical control with more site-specific and need-based pest management.

The choice of pesticide is another important factor in export-oriented production. Farmers may obtain pesticide recommendations from different sources, including input dealers, farmer groups and extension agencies. Studies from different parts of India have shown that pesticide dealers often play an important role in farmers' decisions regarding product selection and application (Gaddanakeri et al., 2023; Ali et al., 2022; Vallur et al., 2023). At the same time, gaps in knowledge regarding pesticide residues, pre-harvest intervals (PHI), safe handling, and other aspects of pesticide use have been reported among farmers in several regions (Kumar et al., 2023; Prasad et al., 2023; Krishna et al., 2022). These observations are relevant to export production because farm-level pesticide decisions ultimately influence the chemical profile of harvested fruit.

The problem becomes more important when several pesticides are applied repeatedly or in combination. Farmers may also apply more than one pesticide in a single spray operation to address multiple pest and disease problems. Such practices require careful attention to label directions, compatibility, and dosage because inappropriate combinations can affect pesticide performance or cause unwanted effects. Repeated use of pesticides from limited chemical groups may also increase selection pressure on pest populations and contribute to resistance development. Therefore, effective export-oriented crop protection requires not simply a reduction in pesticide use, but more rational selection and application based on pest incidence, registered uses, recommended doses, and appropriate intervals.

From an export perspective, pesticide application must also be considered in relation to residue compliance and traceability. The recent assessment of the Indian pomegranate export sector identified pesticide compliance and traceability as important concerns raised by industry stakeholders. The report noted the need for stronger field-level documentation, residue management, and farmer-level capacity building to meet the requirements of high-value international markets (Rao et al., 2026). This indicates that export readiness begins at the production stage rather than only at the packhouse or export point.

The importance of this issue is also reflected in the limited awareness of residue-related requirements reported among pomegranate growers. In the Maharashtra survey, only 21.3 per cent of growers were aware of maximum residue limits (MRLs), while 78.7 per cent were unaware of them. Similarly, only a small proportion of growers reported using economic threshold level-based decisions for pesticide application, despite a relatively high proportion reporting use of recommended doses. These findings suggest that following the recommended dose alone does not necessarily ensure need-based pesticide application or compliance with residue requirements. The observations are consistent with earlier reports of gaps in farmers' knowledge regarding pesticide residues and PHI (Kumar et al., 2023; Prasad et al., 2023; Krishna et al., 2022).

Therefore, pesticide management in Indian pomegranate production needs to be viewed as a part of the export-quality system rather than solely as a pest-control practice. Appropriate pesticide selection, need-based application, adherence to PHI, proper record-keeping, and awareness of residue standards can help connect farm-level crop protection with the requirements of export markets. The relationship between pesticide use and export performance becomes particularly important because residues that remain within one regulatory system may not necessarily satisfy the requirements of another market. This provides the basis for examining pesticide residues and differences in MRL requirements as a separate factor influencing the international marketability of Indian pomegranates.

V. PESTICIDE RESIDUES AND MRL COMPLIANCE IN INDIAN POMEGRANATE

The presence of pesticide residues in harvested pomegranate has received increasing attention because residue compliance is closely linked with food safety and access to international markets. Pomegranate is produced under intensive crop-protection programmes, and residues may remain on or within the fruit depending on the pesticide used, application frequency, dose, and interval between the final application and harvest. Therefore, residue monitoring is an important part of assessing the suitability of pomegranate for markets where pesticide standards are strictly regulated (Kolekar et al., 2011; Kottadiyil et al., 2023; Aralimarad et al., 2024). Early monitoring studies in India indicated that residue compliance could be a significant concern in export-oriented pomegranate production. Kolekar et al. (2011) analysed 179 export-oriented samples collected from major pomegranate-growing areas of Maharashtra and Karnataka and screened them for 86 pesticide residues. About one-third of the samples had no detectable residues, while nearly half contained residues within the prescribed limits. However, approximately one-fifth of the samples exceeded the European Union MRLs, with the proportion of non-compliant samples increasing substantially between the two years of observation. Several fungicides, together with some organophosphate and neonicotinoid insecticides, contributed to the observed violations.

Findings from other Indian studies have also shown that residue occurrence varies considerably among production regions and sampling periods. Pujeri et al. (2011), while analysing only five composite samples from Bijapur, detected residues in four samples, with several pesticide concentrations exceeding the European Union MRLs. In contrast, a more recent market survey by Kottadiyil et al. (2023) reported that 88.8 per cent of the analysed pomegranate samples contained residues below the prescribed MRLs, although bifenthrin, fenvalerate and cypermethrin were frequently detected. Aralimarad et al. (2024) similarly detected several pesticide residues in pomegranate from Kalyana, Karnataka. Despite the occurrence of residues, their dietary risk assessment indicated that the detected concentrations did not result in significant acute or chronic health risks. These findings show that residue detection alone should not be interpreted as evidence of unacceptable consumer risk; the concentration of the residue and the applicable regulatory limit must also be considered. An important issue in export-oriented production is that MRLs are not necessarily identical across regulatory systems. Codex establishes international MRLs, while individual importing regions may apply their own regulatory requirements. In India, pesticide MRLs are prescribed by the Food Safety and Standards Authority of India (FSSAI), whereas the European Union follows its own harmonized regulatory framework. Consequently, a residue concentration that complies with one regulatory system may not necessarily comply with the requirements of an importing market (Ambrus and Yang, 2016; Dureja et al., 2015; Pasupuleti et al., 2022). Differences between Indian and European requirements have been specifically noted for certain pesticides in pomegranate, including carbendazim, creating additional challenges for export-oriented residue management (Mohapatra and Lekha, 2016).

This regulatory variation is particularly important for Indian pomegranate because export markets may impose stringent requirements on both pesticide residues and documentation of production practices. Recent stakeholder-based analysis of the Indian pomegranate export sector identified residue compliance and traceability as important concerns for exporters, particularly in relation to high-value markets. The same assessment highlighted the need for better field-level documentation, residue testing, and farmer training on Good Agricultural Practices and MRL management (Rao et al., 2026).

Thus, pesticide-residue compliance cannot be considered only as a post-harvest laboratory issue. It begins with pesticide selection at the farm level and is influenced by the choice of molecule, application frequency, dose, timing, and adherence to the pre-harvest interval. Regular monitoring of residues, together with proper farm records and awareness of the requirements of the intended export market, is therefore important for maintaining consistent compliance. The available literature indicates that residue occurrence in Indian pomegranate is well documented, but geographically broad and continuous monitoring remains necessary to understand changing residue patterns and their implications for export trade.

The residue issue also needs to be examined alongside the broader export chain. Even when fruit meets the required residue limits, export consignments must satisfy other quality, phytosanitary, traceability, and handling requirements. This indicates that residue compliance is one component of export readiness rather than an isolated factor, leading to the need to consider the analytical monitoring, regulatory standards and market-access requirements together.

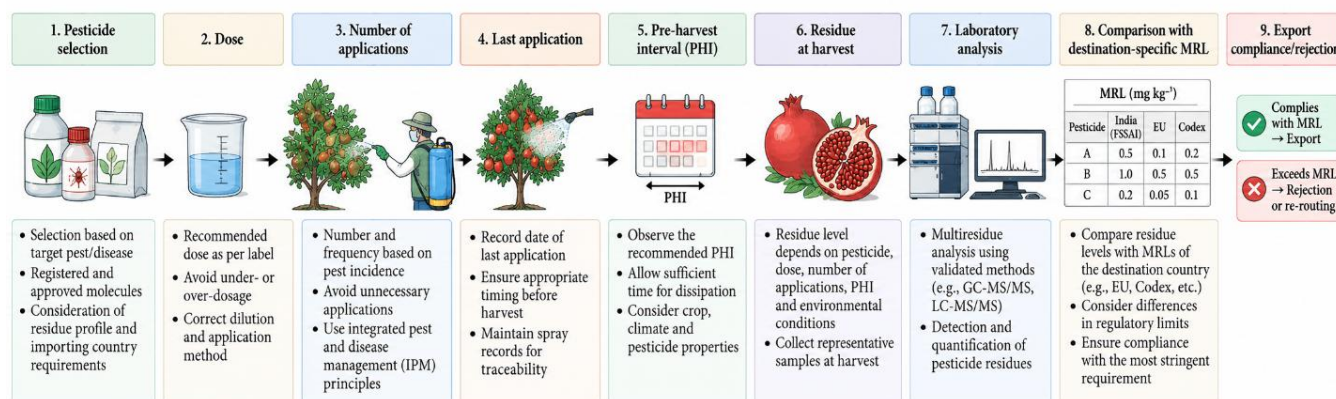


FIGURE 2: Pathway from farm-level pesticide use to residue monitoring, MRL compliance and export-market acceptance.

VI. ANALYTICAL APPROACHES FOR MONITORING PESTICIDE RESIDUES IN POMEGRANATE

Reliable residue monitoring depends on analytical methods capable of detecting a wide range of pesticides at low concentrations in a chemically complex fruit matrix. Pomegranate contains pigments, sugars, organic acids, and other matrix components that can interfere with extraction and instrumental determination. For this reason, residue analysis generally involves careful sample preparation followed by chromatographic separation and sensitive detection. The development of multiresidue methods has made it possible to examine several pesticide groups in a single analytical procedure, which is particularly useful for surveillance of commercially produced fruit (Banerjee et al., 2008; Satpathy et al., 2014).

The QuEChERS approach has become widely used for multiresidue analysis of fruits and vegetables because of its relatively simple extraction procedure, rapid processing and suitability for simultaneous determination of multiple compounds. The method generally involves homogenisation of the sample, extraction with acetonitrile, salt-assisted partitioning and subsequent clean-up, with modifications introduced where necessary to reduce matrix interference (Pszczolińska and Kociołek, 2022; Zhang et al., 2025). Its application to pomegranate has enabled the development of methods capable of detecting pesticides belonging to different chemical groups at concentrations relevant to regulatory monitoring.

Earlier analytical studies demonstrated the feasibility of multiresidue detection in pomegranate using gas chromatographic techniques. Banerjee et al. (2008) developed a method for the determination of 82 pesticides in pomegranate, apple and orange using ethyl acetate extraction, dispersive clean-up and liquid chromatography-tandem mass spectrometry. The method produced acceptable recoveries and reproducibility for most of the compounds examined. Savant et al. (2010) subsequently developed a GC-ion trap MS/MS method covering 50 pesticides in grapes, pomegranate and mango, demonstrating the capability of the approach to quantify residues at concentrations below relevant European Union MRLs.

With the increasing need to analyse pesticides having different physicochemical properties, both gas chromatography and liquid chromatography have become important complementary techniques. Satpathy et al. (2014) reported a QuEChERS-based GC-MS/MS method for simultaneous determination of 82 pesticides in grape and pomegranate. Other investigations have applied modified QuEChERS procedures with GC-MS or liquid chromatographic methods for specific pesticide groups in pomegranate (Mohapatra, 2014; Bilehal et al., 2014). These developments are important because no single instrumental platform is equally suitable for all pesticide classes.

More recent multiresidue analysis increasingly combines GC-MS/MS and LC-MS/MS to provide broader analytical coverage. Such approaches allow relatively non-polar and volatile compounds as well as polar and thermally less stable pesticides to be examined within the same monitoring programme. The importance of this combined approach is evident from recent pomegranate residue investigations in which large numbers of pesticides were screened using complementary chromatographic techniques (Kottadiyil et al., 2023; Aralimarad et al., 2024). Method validation is equally important because the analytical result forms the basis for judging whether a consignment complies with an applicable MRL. Validation generally considers parameters such as specificity, linearity, recovery, precision, matrix effects, and limits of detection and quantification. Validation against internationally accepted guidance, together with appropriate quality-control procedures, supports the reliability of residue results used for regulatory decision-making (Sharma et al., 2021).

The progress in analytical methodology has strengthened the ability to detect pesticide residues at trace concentrations, but analytical capacity alone cannot ensure export compliance. Sampling strategy, representativeness of the samples, selection of target pesticides and comparison with the correct regulatory standard are equally important. Differences in pesticide-use patterns between production regions can also result in different residue profiles. Therefore, continuous field and market surveillance using validated multiresidue methods is necessary to generate reliable information for residue management and to identify potential compliance problems before fruit enters export channels (Kolekar et al., 2011; Kottadiyil et al., 2023). Taken together, the literature shows that considerable progress has been made in the analytical detection of pesticide residues in pomegranate. The remaining challenge is to connect this analytical information with farm-level pesticide practices, regulatory requirements and export-market surveillance. Such integration is essential because the objective of residue analysis in an export system is not merely to detect chemicals, but to provide dependable evidence that the harvested fruit meets the requirements of the intended market.

VII. DIETARY RISK ASSESSMENT OF PESTICIDE RESIDUES: FOOD SAFETY AND EXPORT COMPLIANCE

The detection of pesticide residues in pomegranate does not by itself indicate an unacceptable risk to consumers. The significance of a detected residue depends on its concentration, the amount of fruit consumed, the toxicological reference value of the pesticide and the population group considered. Dietary risk assessment therefore provides a different perspective from MRL compliance, as it estimates the potential exposure of consumers under specified consumption conditions (Aralimarad et al., 2024; Parmar et al., 2025).

Recent studies on pomegranate have used approaches such as Estimated Daily Intake (EDI), Estimated Short-Term Intake (ESTI), Hazard Quotient (HQ) and Hazard Index (HI) to assess chronic, acute and cumulative dietary exposure. Aralimarad et al. (2024) reported that although pesticide residues were detected in pomegranate samples from Kalyana Karnataka, the estimated hazard quotient and hazard index values remained below one, indicating that the exposures considered in that assessment were below the corresponding toxicological reference values. Similar findings have been reported by Parmar et al. (2025), where residue occurrence and regulatory exceedance did not necessarily translate into a corresponding increase in estimated dietary risk.

The distinction between residue compliance and dietary risk is particularly important for export-oriented pomegranate production. An MRL is a regulatory limit established for a specific pesticide and commodity under a particular regulatory system, whereas an HQ or HI compares estimated dietary exposure with a toxicological reference value. Therefore, a sample may exceed the MRL established by an importing country even when the estimated dietary exposure remains below the relevant toxicological reference value. Conversely, compliance with an MRL should not be interpreted as evidence that residue monitoring is unnecessary, because the MRL primarily serves a regulatory and food-production control function (Ambrus and Yang, 2016; Dureja et al., 2015; Pasupuleti et al., 2022).

This distinction becomes more relevant when multiple pesticide residues occur in the same fruit sample. Multi-residue occurrence has been reported in pomegranate monitoring studies, with different pesticides occurring simultaneously in individual samples (Kolekar et al., 2011; Kottadiyil et al., 2023). Such findings indicate that assessment based on a single pesticide may not fully describe overall exposure, particularly where several compounds are detected in the same commodity. The use of cumulative indices such as the Hazard Index provides one approach for examining combined exposure under defined assumptions.

These findings should nevertheless be interpreted within the limitations of dietary risk assessment. The calculated exposure depends on the residue concentrations measured in the sampled fruit, the consumption assumptions, body weight and the toxicological reference values used. Consequently, results from one region or sampling period cannot automatically be generalized to all pomegranate-producing areas. Continuous monitoring and periodic reassessment are therefore necessary, particularly when pesticide-use patterns and residue profiles change over time.

From an export perspective, the practical importance of dietary risk assessment lies in its ability to complement, rather than replace, regulatory residue monitoring. Export markets may impose specific MRL requirements, documentation procedures and testing arrangements irrespective of whether a measured residue concentration represents a significant dietary risk. Recent analysis of the Indian pomegranate export sector has therefore emphasized the need to strengthen residue management and field-level compliance in order to satisfy demanding international markets (Rao et al., 2026).

Overall, the available evidence indicates that the presence of pesticide residues and the assessment of consumer dietary risk are related but distinct aspects of pomegranate safety. For India to supply a wider range of international markets, residue management must address both consumer protection and compliance with the regulatory requirements of the destination country. This brings the discussion beyond pesticide residues alone to the wider phytosanitary, certification, traceability and market-access requirements that determine whether produce can successfully enter international markets.

VIII. POST-HARVEST MANAGEMENT, COLD CHAIN AND VALUE-CHAIN CONSTRAINTS

Meeting pesticide and quality requirements at the farm level does not by itself ensure that pomegranate reaches the international market in acceptable condition. After harvest, the fruit passes through several stages involving collection, transportation, cleaning, sorting, grading, packing and storage. Weaknesses at any of these stages can result in physical damage, moisture loss, deterioration in appearance and reduction in shelf life. Therefore, post-harvest handling is an important link between production quality and export quality.

Pomegranate requires careful harvesting and handling because damaged or diseased fruits are generally unsuitable for export. In the export value chain described for Indian pomegranate, fruits are manually harvested and transported in crates to registered packing houses, where they undergo quality inspection, cleaning, sorting and grading. Fruits are then classified according to characteristics such as size, weight, colour and external appearance before packing. Traceability information associated with the farm, plot, packing house and harvest or packing date is also maintained in export-oriented systems.

A major limitation in the present value chain is the inadequate availability of post-harvest infrastructure close to production areas. The recent assessment of the Indian pomegranate sector identified insufficient pre-cooling, grading and washing facilities at the farm or cluster level, along with inadequate cold storage and integrated cold-chain infrastructure. Sorting and grading are still largely manual in many parts of the chain. These limitations can increase the time between harvest and proper handling and may contribute to quality deterioration before the fruit reaches export facilities (Rao et al., 2026).

The lack of coordinated collection and processing infrastructure is another important issue. Production is often connected to markets through pre-harvest contractors or village-level aggregators, while primary grading and packing facilities are not uniformly distributed across production clusters. The 2026 export-sector assessment identified the absence of adequate primary grading and collection centres, limited warehousing and cold-storage capacity, and gaps in transportation and marketing infrastructure as important constraints in the domestic value chain (Rao et al., 2026).

Cold-chain management becomes even more critical when pomegranate is processed into arils. Unlike whole fruit, arils are highly perishable and require rapid cooling and controlled-temperature handling. The export assessment reported that the processing and export of arils require continuous cold-chain facilities from the point of processing through international transport. Limited access to suitable processing, pre-cooling and refrigerated infrastructure can therefore restrict the expansion of this higher-value segment (Gulati et al., 2022; Rao et al., 2026).

The development of value-added products nevertheless provides an additional avenue for improving the utilization of pomegranate production. Arils, juice and other processed products can provide alternatives to dependence on fresh whole-fruit exports. However, value addition also introduces additional requirements related to hygiene, temperature control, packaging and traceability. The sector therefore needs infrastructure that can maintain product quality consistently from production clusters to processing and export points (Gulati et al., 2022; Rao et al., 2026).

Taken together, the available evidence suggests that post-harvest limitations are not simply issues of storage or transportation; they affect the ability to preserve the quality achieved in the orchard. A fruit meeting export specifications at harvest may still lose market value through rough handling, delayed cooling, inadequate grading or breaks in the cold chain. Strengthening packhouse facilities, pre-cooling, refrigerated transport, cluster-level processing and traceability can therefore help connect farm-level production with export-market requirements.

Thus, the relatively small share of Indian pomegranate entering international markets needs to be understood in the context of the entire value chain. Production volume alone does not determine export performance; the ability to consistently preserve quality, document production practices and deliver the fruit in suitable condition is equally important.

IX. PHYTOSANITARY REQUIREMENTS, CERTIFICATION AND MARKET-ACCESS BARRIERS

Even when pomegranate fruit satisfies the required physical and residue standards, entry into an international market depends on compliance with the phytosanitary and import regulations of the destination country. These requirements are intended to reduce the risk of introducing pests and diseases and to ensure that imported produce meets specified safety and quality conditions. For Indian pomegranate, such requirements can become an important barrier when production, documentation, treatment and inspection systems are not sufficiently aligned with those of the importing market (Rao et al., 2026).

Sanitary and phytosanitary (SPS) measures are particularly important for fresh fruit because importing countries may examine both pesticide residues and the possible introduction of economically important pests and diseases. The recent assessment of Indian pomegranate exports reported that stringent SPS requirements in markets such as the European Union and the United States include controls related to pesticide residues, pests and diseases. Non-compliance may result in delays, additional inspection or rejection of consignments (Rao et al., 2026).

Phytosanitary procedures can also differ substantially among destination countries. The recent export assessment highlighted continuing market-access requirements associated with pest-risk analysis, pest-free areas and other phytosanitary conditions for markets including China, Indonesia, Russia and Japan. Such requirements mean that market access depends not only on the quality of the fruit itself but also on whether the exporting country can demonstrate compliance with the specific pest-management and certification conditions established by the importing country (Rao et al., 2026).

Certification is another component of export readiness. Good Agricultural Practices (GAP) provide a framework covering production practices, food safety and other aspects of responsible agricultural production. Certification can therefore provide evidence that the crop has been produced and handled according to defined requirements. However, the cost and technical requirements associated with certification may create difficulties for small and fragmented growers, particularly when access to higher-value markets depends on documented compliance (Rao et al., 2026).

Traceability is closely connected with certification and phytosanitary compliance. Export-oriented supply chains require information that can link the harvested produce with its production and handling history. The recent assessment identified farm-level documentation and traceability as important areas for improvement in Indian pomegranate production, particularly in relation to pesticide management and export-market compliance (Rao et al., 2026).

Packaging and labelling requirements add another layer of compliance. Export markets may prescribe specific information regarding product origin, packaging and other characteristics, while environmental requirements associated with packaging materials can further increase the cost and complexity of export operations. These requirements become more demanding as exporters attempt to enter high-value markets with more detailed quality and traceability expectations (Rao et al., 2026).

The combination of phytosanitary requirements, residue standards, certification, labelling and tariffs therefore creates a broader market-access challenge than any single technical requirement. The 2026 assessment noted that Indian pomegranate exports remain concentrated in a limited number of neighbouring markets, while entry into several higher-value destinations is affected by regulatory and other trade barriers (Rao et al., 2026).

Importantly, these barriers operate across different stages of the supply chain. Farm-level pesticide and pest-management practices influence residue and phytosanitary compliance; packing houses are involved in inspection, grading and documentation; and exporters must coordinate testing, certification, transport and destination-specific requirements. Consequently, strengthening market access requires coordination between growers, producer organisations, packhouses, laboratories, exporters and regulatory agencies rather than addressing each requirement independently (Rao et al., 2026).

Overall, the literature indicates that India's limited export presence cannot be explained only by production or fruit availability. Compliance with destination-specific phytosanitary and certification requirements is an additional stage between producing export-quality fruit and successfully entering the international market.

X. EXPORT DESTINATIONS, MARKET CONCENTRATION AND INTERNATIONAL COMPETITIVENESS

The export performance of Indian pomegranate shows an important difference between the availability of fruit for export and the markets in which that fruit is actually sold. Although India has developed a substantial export trade over the past decade, exports remain concentrated in a limited number of destinations. This concentration is important because different markets offer different levels of price realization and impose different quality, safety and phytosanitary requirements (Rao et al., 2026).

India's pomegranate exports increased from USD 15.57 million in 2010-11 to USD 69.08 million in 2023–24, corresponding to an average annual growth rate of 16.3 per cent over the period. However, export growth slowed during the later years, and the volume exported in 2022–23 declined as the domestic market offered attractive prices to producers. This suggests that the domestic market can compete with exports for available fruit, particularly when international markets involve greater compliance and logistical costs (Rao et al., 2026).

The geographical distribution of exports further illustrates this pattern. During the period reported by the export analysis, the UAE, Bangladesh, Nepal, the Netherlands and Qatar accounted for major shares of India's pomegranate exports, with the UAE and Bangladesh together representing a substantial proportion of export volume. These destinations have helped India develop and maintain export volumes, but the distribution also indicates considerable dependence on a relatively small group of markets (Rao et al., 2026).

At the same time, substantial differences exist in the price realized across destination markets. The country-wise export data for 2023–24 reported realizations of about INR 702 per kg in Switzerland and INR 628 per kg in the United States, compared with approximately INR 126 per kg in the UAE, INR 47 per kg in Nepal and INR 32 per kg in Bangladesh. These differences indicate that destination choice is associated with markedly different levels of value realization, although the higher-priced markets also require compliance with more demanding quality, safety, certification and phytosanitary conditions (Rao et al., 2026).

The present export structure therefore reflects two distinct market segments for Indian pomegranate. Neighbouring and regional markets provide an established outlet for larger export volumes, supported partly by geographical proximity and relatively shorter supply chains. In contrast, distant high-value markets require greater attention to fruit quality, residue compliance, certification, traceability, cold-chain management and destination-specific phytosanitary conditions. The recent export assessment suggests that strengthening these capabilities could support greater participation in high-value markets while retaining existing regional destinations as part of the export base (Rao et al., 2026).

India also shows evidence of international competitiveness in pomegranate exports. The recent ICRIER–APEDA assessment reported a Revealed Comparative Advantage (RCA) greater than one and identified a competitive price position for India. However, the same analysis noted that trade remains constrained by non-tariff measures, including SPS and labelling requirements, tariff disadvantages in some markets and limited product differentiation and branding (Rao et al., 2026). Thus, production capacity and comparative advantage do not automatically result in broad international market penetration.

Another difficulty in assessing the global position of pomegranate is the availability of reliable trade statistics. At the international level, pomegranate is included under the broader HS code 081090, which also covers several other fruits. This prevents direct separation of pomegranate from all commodities classified under the same code and makes detailed country-wise comparison of global pomegranate trade more difficult (Ergun, 2012; Rao et al., 2026).

Market diversification therefore appears closely connected with the broader quality and compliance issues discussed in earlier sections. Access to higher-value destinations depends on producing fruit with consistent size, colour and appearance, maintaining acceptable residue profiles, fulfilling phytosanitary requirements and preserving quality through the supply chain. In this sense, diversification is not simply a matter of identifying new buyers; it requires the production and export system to meet the technical requirements of those markets (Rao et al., 2026).

Overall, the export evidence shows that India has built a growing pomegranate export sector, but much of the trade remains concentrated in regional markets, while higher-value destinations account for relatively smaller quantities. The difference in destination-wise price realization, together with the requirements associated with premium markets, highlights the importance

of improving quality, compliance, traceability and supply-chain performance. These factors provide the basis for examining the major opportunities and strategies for expanding Indian pomegranate exports, including value addition, export-oriented production clusters, market diversification and stronger integration of growers with export supply chains.

Export requirement	Farm  Production and crop management	Packhouse  Sorting, grading, packing and storage	Laboratory  Residue analysis and testing	Exporter  Market access and compliance
 Pesticide use and pre-harvest interval (PHI)	✓	—	—	—
 Residue testing	—	✓	✓	✓
 Traceability (farm to export)	✓	✓	—	✓
 Phytosanitary compliance (pests and diseases)	✓	✓	—	✓
 Certification (e.g., GAP and other schemes)	✓	✓	—	✓
 Packaging and labelling	—	✓	—	✓

 Indicates key responsibility/requirement at this stage — Not a primary responsibility at this stage

FIGURE 3: Destination-specific export requirements and the distribution of key compliance responsibilities across farm, packhouse, laboratory and exporter stages of the pomegranate export chain.

XI. OPPORTUNITIES FOR EXPANDING INDIAN POMEGRANATE EXPORTS

The constraints affecting Indian pomegranate exports also indicate several opportunities for improving the position of the crop in international markets. India already has important production advantages, including a large production base, the widely accepted Bhagwa cultivar and the ability to produce fruit across different cropping seasons. The challenge is to convert these production advantages into consistent export-quality supply through better integration of cultivation, post-harvest handling, compliance and marketing (Prasad et al., 2013; Saroj and Sharma, 2017; Rao et al., 2026).

One important opportunity lies in the expansion of value-added pomegranate products, particularly arils. The available evidence indicates that international demand exists for ready-to-eat arils and other processed products such as juice concentrates, dried products and seed oil. Compared with whole fruit, these products can provide additional avenues for value realization, although their expansion depends on appropriate processing, hygiene, packaging, cold storage and traceability systems (Gulati et al., 2022; Rao et al., 2026).

The development of production-cluster-based export infrastructure could help address several of these requirements simultaneously. Establishing packhouses and processing facilities close to major production areas can reduce unnecessary movement of fruit before primary handling and provide facilities for cleaning, grading, pre-cooling, packaging and storage. The recent export assessment has proposed strengthening such infrastructure through cluster-based systems and improved connections between farms, processing centres and exporters (Rao et al., 2026).

Such an approach may be particularly useful for pomegranate-growing regions of Maharashtra, where large production clusters already exist. The export assessment identified areas such as Solapur and specifically highlighted Sangola as a location with substantial Bhagwa cultivation and experience in export-oriented production. Cluster-level facilities could therefore provide a practical link between growers and export markets by combining primary processing, quality assessment, residue testing and logistics within the production region (Rao et al., 2026).

Market diversification represents another area of opportunity. Current exports are concentrated in a limited number of regional markets, while smaller quantities are shipped to destinations where the reported price realization is considerably higher. Expanding into such markets would require consistent compliance with quality, residue, certification and phytosanitary standards, but diversification could reduce dependence on a small group of destinations and create opportunities for higher-value trade (Rao et al., 2026).

Branding and traceability can support this process by distinguishing Indian pomegranate from competing origins. The recent export assessment noted the importance of certification, traceability and targeted branding, particularly for premium retail markets. Experiences involving traceable and certified Indian aril products suggest that market identity may be strengthened when product quality can be linked with documented production and handling practices (Gulati et al., 2022; Rao et al., 2026).

Varietal improvement is also relevant to long-term export development. Although Bhagwa is widely accepted in international trade, concerns regarding fruit size, uniformity and suitability for different market segments have been reported. The development or selection of clones with stable fruit characteristics suited to particular agro-climatic conditions and export requirements may therefore complement improvements in crop management and post-harvest handling (Prasad et al., 2013; Saroj and Sharma, 2017; Rao et al., 2026).

Crop protection also has a role within this export-oriented approach. Better integration of pest and disease management with residue management can help reduce unnecessary pesticide applications while maintaining fruit quality. Farmer training in Good Agricultural Practices, pesticide selection, MRL requirements and record keeping can strengthen the connection between orchard management and export compliance. The recent export assessment specifically identified farmer training, integrated pest and disease management and stronger field-level compliance as areas requiring continued attention (Rao et al., 2026).

Taken together, these opportunities suggest that expansion of Indian pomegranate exports depends on improvements across the entire supply chain rather than on increasing production alone. Higher export participation will require coordinated progress in fruit quality, residue compliance, traceability, packhouse infrastructure, cold-chain management, value addition, varietal improvement and market development. Such an integrated approach can help convert India's existing production capacity into a more consistent and diversified export supply.

XII. RESEARCH GAPS AND FUTURE DIRECTIONS FOR INDIAN POMEGRANATE EXPORTS

The literature reviewed above shows that India has a strong production base and an established export trade, but the available research is distributed across separate areas such as production, pesticide use, residue monitoring, post-harvest handling and market access. These studies provide useful information on individual constraints, but relatively few studies examine how these factors interact along the complete pomegranate supply chain. The recent ICRIER–APEDA assessment also identified the need to consider production, compliance, infrastructure, processing and market access together when examining India's export potential (Rao et al., 2026).

One important research gap concerns the relationship between farm-level pesticide practices and export compliance. Previous studies have documented pesticide-use patterns and residue occurrence in different pomegranate-growing regions, but these investigations are often limited to specific locations or sampling periods (Elango and Sridharan, 2017; Kolekar et al., 2011; Kottadiyil et al., 2023). There is a need for more systematic studies linking the pesticides actually used by growers with residue levels detected at harvest and, where possible, with the requirements of specific export destinations. Such studies could help identify which production practices contribute most to residue-related non-compliance.

Geographically representative residue surveillance is another area requiring attention. Earlier investigations have provided valuable evidence from Maharashtra, Karnataka, Gujarat and other regions, but the available information remains fragmented with respect to sampling location, season, pesticide coverage and source of fruit (Kolekar et al., 2011; Pujeri et al., 2011; Kottadiyil et al., 2023; Aralimarad et al., 2024). Continued multiresidue monitoring of both field-produced and market-available pomegranate could provide a better understanding of changes in residue profiles over time. Such datasets would also be useful for distinguishing persistent production-related problems from isolated residue findings.

A related gap exists in the integration of residue data with dietary risk assessment and export compliance. Studies have shown that pesticide residues may be detected, and in some cases exceed particular MRLs, while estimated dietary exposure remains below the corresponding toxicological reference values (Aralimarad et al., 2024; Parmar et al., 2025). Further work should therefore continue to distinguish regulatory compliance from dietary-health risk and should examine both aspects when

interpreting residue findings. Comparative studies using Indian regulatory limits alongside the requirements of major importing markets could provide more practical information for export-oriented production (Dureja et al., 2015; Pasupuleti et al., 2022).

Traceability and farm-level documentation also deserve greater research attention. The recent export-sector assessment identified gaps in documentation, pesticide management and compliance capacity in parts of the production system (Rao et al., 2026). However, there is limited published evidence on how farm records, pesticide application histories, residue testing and traceability systems can be integrated into a practical and economically feasible system for small and medium growers. Research on digital or cluster-based traceability models could therefore contribute to improving continuity between farm production, packhouse operations and export certification.

Post-harvest research also needs to move beyond individual technologies and examine the complete chain from harvest to export. Existing evidence identifies shortcomings in pre-cooling, grading, cold storage, transportation and processing infrastructure, while aril products require particularly careful temperature and hygiene management (Gulati et al., 2022; Rao et al., 2026). Further studies could evaluate integrated packhouse and cold-chain models at major production clusters and quantify their effects on fruit quality, post-harvest loss, rejection rates and export value.

Market-specific research is another important need. India's export destinations differ substantially in their price realization, phytosanitary conditions, certification requirements and consumer preferences (Rao et al., 2026). More detailed studies comparing destination markets could help identify the production and supply-chain characteristics required for entry into particular markets rather than treating the international market as a single category. Such research would also help clarify whether the major constraints to market expansion arise at the farm, processing, logistics or policy level.

Finally, greater attention is needed to the potential of value-added products such as arils, juice and other processed forms. The literature and recent sector assessment indicate that these products provide opportunities for diversification, but their expansion is constrained by processing capacity, cold-chain requirements, packaging technology and quality control (Gulati et al., 2022; Rao et al., 2026). Research combining product quality, processing economics, food safety, shelf life and export-market requirements could help determine where value addition can be integrated most effectively into the Indian pomegranate supply chain.

Overall, future research should move towards a more integrated framework in which production practices, fruit quality, pest and disease management, pesticide residues, traceability, post-harvest handling and destination-market requirements are studied as connected components of export readiness. The evidence currently available provides a strong foundation, but greater integration of these research areas is needed to understand why a large production base has not yet translated into a proportionately broader international market presence.

XIII. CONCLUSION

India has a strong foundation for pomegranate export through its large production base, widespread cultivation of Bhagwa, long production season and established access to overseas markets. Yet the relatively small share of production entering international trade shows that production volume alone does not determine export performance. The exportable share of the crop depends on whether fruit consistently meets market requirements for size, colour, appearance, disease freedom, residue compliance, shelf life, traceability and phytosanitary safety. The evidence reviewed in this article indicates that export constraints are interconnected. Pest and disease pressure can increase dependence on pesticides; pesticide selection and application practices influence residue profiles; residue non-compliance can restrict access to particular markets; and inadequate post-harvest handling can reduce the quality of fruit that has already met farm-level requirements. At the same time, certification, traceability, phytosanitary procedures, logistics and market-specific standards influence the cost and feasibility of reaching higher-value destinations. Improving exports therefore requires an integrated production-to-market approach rather than a single intervention. Priority areas include export-oriented crop and pest management, better control of pesticide residues, systematic residue surveillance, stronger farm-level documentation and traceability, improved packhouses and cold-chain infrastructure, expansion of value-added products such as arils, and diversification into markets with sustainable demand. Research should increasingly examine these factors together so that farm practices, food safety, post-harvest management and destination-market requirements can be considered within a common framework. The central challenge for India is not simply to produce more pomegranate, but to increase the proportion of fruit that can move efficiently and consistently from the orchard to compliant, higher-value international markets. Strengthening this connection across the entire value chain can provide a more practical basis for expanding Indian pomegranate exports.

AUTHOR(S) CONTRIBUTION STATEMENT

Durgesh Kailas Narwade: Conceptualization, Methodology, Investigation, Formal analysis, Writing-original draft, Visualization, Writing-review & editing. B. V. Deore: Writing-review & editing, Data curation, Investigation. S. B. Deore: Review & editing.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing, grammar correction, and improvement of clarity and readability. The final manuscript was critically reviewed and verified by the authors, who take full responsibility for its content.

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REFERENCES

- [1] Ali, I., Rahman, S. Z., Qamar, A., & Khan, M. S. (2022). Survey-based study on farmers' knowledge and pattern of using insecticide on different crops in Aligarh District of Uttar Pradesh, India. *International Journal of Human and Health Sciences*, *6*(2), 193-199. <https://doi.org/10.31344/ijhhs.v6i2.445>
- [2] Ambrus, Á., & Yang, Y. Z. (2016). Global harmonization of maximum residue limits for pesticides. *Journal of Agricultural and Food Chemistry*, *64*(1), 30-35. <https://doi.org/10.1021/jf505347z>
- [3] Anbazhagan, P., Wilson, A., Nallasamy, V., & Ramanathan, S. (2022). Assessment on knowledge and perception regarding health risks of pesticide usage among farmers. *International Journal of Public Health Science*, *11*(4), 1424. <https://doi.org/10.11591/ijphs.v11i4.21230>
- [4] APEDA. (2023). *Agricultural and Processed Food Products Export Development*. <https://apeda.gov.in/>
- [5] Aralimarad, P., Bedar, J., Mahato, S., Hanchinal, S. G., Naik, N., Shwetha, U., Pavankumar, K., Naveenkumar, P., Gavai, A., Rat, R. S., & Patil, M. (2024). Simultaneous determination of multi-class pesticide residues in solanaceous vegetables and selected fruits using LC-MS/MS and potential impact on consumer health with measurement uncertainty. *Research Square*. <https://doi.org/10.21203/rs.3.rs-5199827/v1>
- [6] Balikai, R. A., Kotikal, Y. K., & Mani, M. (2022). Pests and their management in pomegranate. In M. Mani (Ed.), *Trends in horticultural entomology*. Springer. https://doi.org/10.1007/978-981-19-0343-4_29
- [7] Balikai, R. A., Kotikal, Y. K., & Prasanna, P. M. (2011). Status of pomegranate pests and their management strategies in India. *Acta Horticulturae*, *890*, 569-583. <https://doi.org/10.17660/ActaHortic.2011.890.81>
- [8] Banerjee, K., Patil, S. B., Patil, S. H., Dasgupta, S., Savant, R., & Adsule, P. G. (2008). Single-laboratory validation and uncertainty analysis of 82 pesticides determined in pomegranate, apple, and orange by ethyl acetate extraction and liquid chromatography/tandem mass spectrometry. *Journal of AOAC International*, *91*(6), 1435-1445. <https://doi.org/10.1093/JAOAC/91.6.1435>
- [9] Bilehal, D., Chetti, M. B., Sung, D. D., & Goroji, P. T. (2014). Reversed-phase UPLC method for the determination of monocrotophos, thiram, carbendazim, carbaryl, and imidacloprid pesticides in mango and pomegranate by QuEChERS method. *Journal of Liquid Chromatography & Related Technologies*, *37*(12), 1633-1643. <https://doi.org/10.1080/10826076.2013.803205>
- [10] Chauhan, N. N., & Gupta, D. (2024). Evaluation of IPM modules against pomegranate fruit borer *Deudorix epijarbas* (Moore). *Indian Journal of Entomology*, *86*(2), 557-561. <https://doi.org/10.55446/IJE.2023.815>
- [11] Directorate General of Foreign Trade Ministry of Commerce and Industry Government of India. (2025). Dgft.gov.in. <https://www.dgft.gov.in/CP/index.jsp>
- [12] Doddaraju, P., Kumar, P., Gunnaiah, R., Gowda, A. A., Lokesh, V., Pujer, P., & Manjunatha, G. (2019). Reliable and early diagnosis of bacterial blight in pomegranate caused by *Xanthomonas axonopodis* pv. *punicae* using sensitive PCR techniques. *Scientific Reports*, *9*, 10097. <https://doi.org/10.1038/s41598-019-46588-9>
- [13] Dureja, P., Singh, S. B., & Parmar, B. S. (2015). Pesticide maximum residue limit (MRL): Background, Indian scenario. *Pesticide Research Journal*, *27*(1), 4-22.
- [14] Elango, K., & Sridharan, S. (2017). Assessment of farmer's perception on pesticides usage pattern and knowledge of pest management in pomegranate under high-density planting at major pomegranate growing districts of Tamil Nadu. *Trends in Biosciences*, *10*(45), 9260-9263.
- [15] Ergun, M. (2012). Pomegranates. In M. Siddiq (Ed.), *Tropical & subtropical fruits: Postharvest physiology, processing and packaging* (1st ed., pp. 529-548). John Wiley & Sons Inc.

- [16] Gaddanakeri, S., Pradeep, S., Deshmukh, S., Shivanna, B. K., Sridhara, S., Thippesha, D., & Fakrudin, B. (2023). Insecticide usage pattern and knowledge level of farmers on insecticides handling to manage *Leucinodes orbonalis* Guenee in brinjal across different localities. *International Journal of Environment and Climate Change*, *13*(8), 777-784. <https://doi.org/10.9734/ijec/2023/v13i82010>
- [17] Gulati, A., Ganguly, K., & Harsh Wardhan. (2022). *Agricultural value chains in India*. Springer Nature.
- [18] Hem, L., Park, J.-H., & Shim, J.-H. (2010). Residual analysis of insecticides (lambda-cyhalothrin, lufenuron, thiamethoxam and clothianidin) in pomegranate using GC- μ ECD or HPLC-UV. *Korean Journal of Environmental Agriculture*, *29*(3), 257-265. <https://doi.org/10.5338/KJEA.2010.29.3.257>
- [19] Kahramanoglu, I. (2019). Trends in pomegranate sector: Production, postharvest handling and marketing. *International Journal of Agriculture, Forestry and Life Sciences*.
- [20] Kambrekar, D. N., & Biradar, A. P. (2015a). Field efficacy of insecticides in the management of pomegranate aphid, *Aphis punicae* (Passerini). *Acta Horticulturae*, *1089*, 153-159. <https://doi.org/10.17660/ActaHortic.2015.1089.17>
- [21] Kambrekar, D. N., Biradar, A. P., & Karabhantanal, S. S. (2015b). New insecticides for the management of pomegranate fruit borer, *Deudorix isocrates* (F.). *Indian Journal of Entomology*, *77*(3), 240-244. <https://doi.org/10.5958/0974-8172.2015.00050.4>
- [22] Kolekar, V. S., Wakure, D. D., Raut, P. N., & Utture, S. C. (2011). Monitoring of pesticide residues in exportable pomegranate fruits. *Acta Horticulturae*, *890*, 547-555. <https://doi.org/10.17660/ActaHortic.2011.890.77>
- [23] Kottadiyil, D., Mehta, T., Thasale, R., & Sivaperumal, P. (2023). Determination and dietary risk assessment of 52 pesticide residues in vegetable and fruit samples by GC-MS/MS and UHPLC-QTOF/MS from Gujarat, India. *Journal of Food Composition and Analysis*, *115*, 104957. <https://doi.org/10.1016/j.jfca.2022.104957>
- [24] Krishna, T. M., Devaki, K., Kumar, K. K., & Prasanthi, L. (2022). Dissipation kinetics and the pre-harvest residue of chlorantraniliprole in pigeon pea (*Cajanus cajan* L.) succulent pods using ultra-high-performance liquid chromatography with photodiode array detector (UHPLC-PDA). *Open Journal of Analytical and Bioanalytical Chemistry*, *6*(1), 013-017. <https://doi.org/10.17352/ojabc.000025>
- [25] Kulkarni, S. R., Kadam, J. R., & Chavan, A. P. (2007). Preliminary studies on the efficacy of *Verticillium lecanii* (Zimmermann) against mixed populations of mealy bugs on pomegranate. *Pest Management in Horticultural Ecosystems*, *13*(1).
- [26] Kumar, P., LNU, D., & Singh, R. P. (2023). *Farmer's attitudes on pesticide-use and pest-management practices: A case study of vegetable-cultivators in the vicinity of Lucknow, India*. <https://doi.org/10.52679/bi.e202312002>
- [27] Mohapatra, S. (2014). Residue dynamics of chlorpyrifos and cypermethrin in/on pomegranate (*Punica granatum* L.) fruits and soil. *International Journal of Environmental Analytical Chemistry*, *94*, 1394-1406. <https://doi.org/10.1080/03067319.2014.954564>
- [28] Mohapatra, S., & Lekha, S. (2016). Residue level and dissipation of carbendazim in/on pomegranate fruits and soil. *Environmental Monitoring and Assessment*, *188*(7), 406. <https://doi.org/10.1007/s10661-016-5404-2>
- [29] Parmar, K. D., Rathod, P. H., Kalasariya, R. L., Pandya, M. J., Patel, M. R., Chawla, S., & Patel, M. P. (2025). Dissipation and risk assessment of a combination product of chlorantraniliprole + abamectin and spirotetramat in pomegranate fruit and juice. *Biomedical Chromatography*, *39*(9), e70174. <https://doi.org/10.1002/bmc.70174>
- [30] Pasupuleti, V. V., Majji, K. R., Bagade, P., & Kachireddy, V. N. S. R. (2022). Study on existence of pesticides in Indian grapes and their compliance for export to EU nations through advanced analytical instrumentation. *Research Journal of Chemistry and Environment*, *26*(10), 75-88. <https://doi.org/10.25303/2610rjce075088>
- [31] Pienaar, L., & Boonzaaij, J. (2018). *Drought policy brief: Western Cape agriculture*. Bureau for Food and Agricultural Policy, Western Cape Department of Agriculture.
- [32] Prasad, A., Nagda, G., Syed, N., & Kumar, A. (2023). A detailed survey on awareness, knowledge and practice of pesticides used against various vegetables, fruits and cereal crops grown in and around Udaipur region of South Rajasthan, India. *Bulletin of Pure and Applied Sciences—Zoology*, *42*(1), 43-63. <https://doi.org/10.48165/bpas.2023.42A.1.6>
- [33] Prasad, K. S., Mukunda, G., Mohankumar, A., & Yathiraj, K. (2013). Bhagwa a promising variety of pomegranate for dry. *International Journal of Agricultural Sciences*.
- [34] Pszczolińska, K., & Kociołek, B. (2022). The pesticide residue analysis in commodities with high content of chlorophyll based on the quick, easy, cheap, effective, rugged, and safe method: A review. *Journal of Separation Science*, *45*(1), 149-165. <https://doi.org/10.1002/jssc.202100304>
- [35] Pujeri, U. S., Yadawe, M., Hiremath, S. C., & Pujar, A. S. (2011). Monitoring of pesticide residues in pomegranate of Bijapur District, Karnataka. *Research Journal of Chemistry and Environment*, *15*(2), 355-358.
- [36] Rao, S., Bhargava, A., Rohtagi, A., & Gulati, A. (2026). *Strategies to boost India's pomegranate exports*. Indian Council for Research on International Economic Relations (ICRIER).
- [37] Saroj, & Sharma, B. D. (2017). *Cultivar Bhagwa: Revolutionizing*. ICAR-Central Institute for Arid Horticulture.
- [38] Satpathy, G., Tyagi, Y. K., & Gupta, R. K. (2014). Development and validation of multi-residue analysis of 82 pesticides in grapes and pomegranate as per the requirements of the European Union (EU) and Codex Alimentarius using GC-MS/MS with compound-based screening. *American Journal of Food Science and Technology*, *2*(2), 53-61. <https://doi.org/10.12691/ajfst-2-2-2>
- [39] Sharma, A. K., Dubey, J., Katna, S., Shandil, D., Brar, G. S., & Singh, S. (2021). Validation of analytical methods used for pesticide residue detection in fruits and vegetables. *Food Analytical Methods*, *14*(9), 1919-1926. <https://doi.org/10.1007/s12161-021-02027-y>
- [40] UN Comtrade. (2024). *UN Comtrade*. <https://comtradeplus.un.org/>
- [41] Vallur, J. H. V., Cherukuri, S. R., Chiranjeevi, Ch., Varma, P. K., & Rao, V. S. (2023). Knowledge, attitude and behaviour of paddy growers towards use and handling of pesticides in Krishna Western Delta area of Guntur District of Andhra Pradesh, India. *Ecology, Environment & Conservation*, *29*(3), 1055-1060. <https://doi.org/10.53550/eec.2023.v29i03.020>
- [42] Zhang, X., Wang, X., Chen, J., Zhang, Z., Ding, H., Du, X.-Z., & Lu, X.-Q. (2025). Simultaneous detection of 34 pesticide and metabolite residues in vegetables and fruits using improved QuEChERS-gas chromatography-tandem mass spectrometry with carboxylated multi-walled carbon nanotubes. *Chinese Journal of Chromatography*, *43*(10), 1145-1153. <https://doi.org/10.3724/sp.j.1123.2025.02001>