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A review on organic amendments for sustainable production of Pomelo

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ABSTRACT

This review synthesizes current evidence on how organic amendments support sustainable cultivation of pomelo (*Citrus maxima*). We examine compost, vermicompost, biochar, biofertilizers, and low-residue biopesticides in relation to soil function, nutrient cycling, yield, fruit quality, and environmental outcomes. Across studies, organic inputs consistently improve soil structure, nutrient retention, and microbial activity while reducing dependence on synthetic fertilizers and pesticides. We summarize practical, orchard-ready strategies for pomelo – building soil organic matter, co-applying biochar with organics, targeted microbial inoculation at establishment, and integrating biopesticides within integrated pest management calendars – and outline implementation using soil and leaf diagnostics. Notably, most reported benefits are generalized from other crops; robust pomelo-specific, long-term field trials that quantify yield, quality, and farm economics remain limited. We, therefore, propose a research agenda prioritizing multi-season, orchard-scale evaluations, and decision-relevant economic metrics. Overall, organic amendments provide a credible pathway to align consumer health, environmental stewardship, and grower viability in pomelo systems while addressing soil degradation and pollution.

1. INTRODUCTION

The Green Revolution focused on the sustainability of agricultural production by modern agricultural methods to feed the ever-increasing population with minimal effort. In the process of feeding humanity, the dependence of modern agriculture on synthetic fertilizers and pesticides has caused deleterious consequences on its consumers, and an ever-growing dependence on them has led to irreversible damage to soil, water, and biological resources [1]. Various concerns have been raised against the use of synthetic chemicals in agriculture and their adverse effects, ranging from acute to chronic impact on the biotic community and abiotic community [2,3]. Numerous methodological and analytical approaches have been established to quantify the impact of agricultural methodology implemented on the surrounding environment, and the outcome of modern agriculture has proven to be deleterious [4]. The primary objective of any occupation needs to follow the basic rules of environmental, social, and economic sustainability, not just human survival. Mankind has been harnessing nature's potential for various purposes for centuries, and the fertility of the land was never deteriorated as much as the use of synthetic fertilizers and pesticides. The long-term fertility of the soil can be maintained by following the classical method of farming "The organic farming" by maintaining organic matter, careful mechanical intervention, implementing biological nitrogen fixation, effective organic material recycling, control of weed, diseases and pest by crop rotations, natural predators, diversity, organic manuring, using resistant varieties and excludes the use of synthetic pesticides, fertilizers, growth promoters, and livestock feed additives [5]. Multiple studies have confirmed that organic farming in tree orchards has positively influenced tree growth, nutritional quality of fruits, and productivity, along with maintaining the fertility of the soil [6]. There is an increasing popularity/demand for organically grown fruits, especially in the developed countries, and the same is creeping into the developing countries as they are found to be healthier than conventionally produced fruits [7].

Various families of fruits and vegetables are consumed by humans, and these provide a mix of nutrients and boost our immune system. A diet rich in fruits and vegetables is known to prevent various diseases, and it helps in keeping a healthy appetite. *Citrus* is an important crop and is one of the largest produced fruits. They are an important component of the human diet and a major component during illness due to its high concentration of Vitamin C, sodium, folic acid, potassium, flavonoids, coumarins, pectin's, dietary fibres, and cholesterol-free [8]. It is grown in suitable climates ranging from tropical, subtropical, and borderline subtropical/temperate. China is the largest producer of *Citrus* in the world, followed by USA, India. Southeast Asia is considered to be the center of origin as it houses a vast genetic diversity [9]. The genus *Citrus* L., belonging to the subtribe Citrineae, is the sole source of the fruit belonging to the orange subfamily Aurantioideae (with two tribes and 33 genera) of the family Rutaceae. Mandarin (*Citrus reticulata*

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Blanco), sweet orange (*Citrus sinensis* (L.) Osbeck), grapefruit (*Citrus paradisi* Macf.), lemon (*Citrus limon* (L.) Burm. f.), and lime (*Citrus aurantiifolia* (Christm.) Swingle) are the most commercially important fruits of this genus [10]. Polyembryony is observed in most of the *Citrus* genus and the adventive embryos are produced from the nucellus. Adventive nucellar embryony trait is considered by taxonomists for classification, among them *Citrus medica* (citron) and *Citrus maxima* (pomelo) species are strictly monoembryonic while *C. reticulata* is polyembryonic [9]. Despite extensive work on pomelo's nutrition, diversity, and taxonomy, very few studies examine agronomic pathways to make pomelo commercially competitive under sustainable/organic systems. This gap is critical because input-intensive agriculture has well-documented environmental and health costs [1-3], while organic orchard management can improve tree performance, fruit quality, and soil fertility [6] amid rising demand for organic fruit [7,11]. Accordingly, this study tests an integrated, eco-friendly orchard protocol for pomelo and quantifies effects on fruit quality, size uniformity, marketable yield, and soil fertility, providing a pathway to commercially viable, environmentally responsible production.

Pomelo (Scientifically known as *Aurantium maximum* Burm. Ex Rumph, *Citrus aurantium* L. Var *grandis* L., *Citrus decumana* L., *Citrus grandis* Osbeck, and *Citrus pamplemos*) being a wild species of the Rutaceae family are grown as a tropical Citrus fruit and commonly classified based on fruit pulp as white (common) or red (pigmented) [12,13]. In most of the countries, it is grown in backyard gardens and not a regular crop [14]. Although it is the largest fruit of *Citrus* group, it has not attained commercial importance despite its health and nutritional benefits [15]. In fact, the popularity of pomelo lies in its greater tolerance to insect and diseases than other *Citrus* fruits and for its fruit quality (slightly acidic with a hint of bitterness) and is one of the most cultivated fruits in Southeast Asia and other parts of the world [16]. China is the leading producer of Pomelo, followed by United States and other South-eastern counties if Asia [17]. However, number of trees with good quality fruit is very negligible in comparison to the inferior ones, and even then, large variability exists across the globe due to self-incompatibility. A huge diversity is observed based on the morphology and molecular markers [15].

2. SUSTAINABLE PRODUCTION OF POMELO

2.1. Origin and Diversity of Pomelo

Pomelo (*C. maxima*), a prominent species within the *Citrus* genus, holds considerable importance due to its status as a principal progenitor in the evolution of numerous cultivated *Citrus* varieties. The species is thought to have originated in Southeast Asia, specifically within the Malayan and East Indian archipelagos. From these initial regions, the pomelo disseminated to various locales, including South China and India, before ultimately making its way to Europe and the Americas.

The origin of the *Citrus* genus is believed to trace back millions of years to Southeast Asia, with *C. maxima* Burm. Merr. (commonly known as pomelo) identified as one of its primary progenitors, alongside *C. reticulata* Blanco, *C. medica* L., and *Citrus* micrantha Wester [Table 1]. Numerous scholarly sources indicate that the cultivated species of *Citrus* are the result of hybridization among these four foundational species [18], which posited that "pomelo is indigenous to the Malaya and East Indian archipelagos," from which it subsequently disseminated to other Asian nations, followed by its introduction to Europe and the Americas [12].

Table 1: Pomelo origin and cultivation details.

Aspect	Details	References
Origin of *Citrus*	Southeast Asia, millions of years ago	[18]
Key originators of *Citrus*	*Citrus maxima* Burm. Merr, *Citrus reticulata* Blanco, *Citrus medica* L., *Citrus micrantha* Wester	[18]
Indigenous region of pomelo	Malaya and East Indian archipelagos	[12]
Historical spread	Spread to Asia, Europe, America	[12]
Cultivation duration	Over 3000 years	
Countries cultivating pomelo	Vietnam, China, India, Bangladesh, Indonesia, Cambodia, Japan, Chile, Sri Lanka, Malaysia, Philippines, Thailand, Nepal	[15,21,22]
Historical documentation of growth and consumption	Palestine and Spain (1187 A.D.), Italy (1646), Jamaica (1696)	[10,23,24]
Challenges in genetic diversity	Decreased genotypic variability due to domestication and elimination of undesirable traits	[25]
Efforts to analyze genetic variability	Recent attempts in Vietnam, China, Indonesia, and others to analyze phenotype and genotype traits	[9,26]

The extensive diversity of cultivated *Citrus* species, characterized by variations in phenotypic, phytochemical, and molecular traits, can be attributed to the ease of cross-fertilization and hybridization among these species [18]. Pomelo has been cultivated for over 3,000 years, leading to the development of numerous varieties; however, limited efforts have been made to comprehensively evaluate its genetic diversity [19]. The precise site of origin for pomelo remains ambiguous, as multiple countries within Southeast Asia assert claims to this designation. Pomelo is cultivated in both home gardens and commercial orchards across various nations, including Vietnam, China, India, Bangladesh, Indonesia, Cambodia, Japan, Chile, Sri Lanka, Malaysia, the Philippines, Thailand, and Nepal [15,20-22].

Historical records indicate that the growth and consumption of pomelo were documented in Palestine and Spain as early as 1187 A.D. [23], followed by mentions in Italy [24] and Jamaica in 1696 [10]. Dr. David Fairchild and other horticultural enthusiasts introduced pomelo plants and seeds to the United States, where they were initially cultivated in greenhouses; however, only a few specimens survived. The fruits produced from these plants were of inferior quality, but when grafted onto grapefruit trees, they yielded fruits of significantly higher quality.

The prolonged selection for specific traits during the domestication process, coupled with the elimination of undesirable traits, has raised concerns regarding the potential decrease in genotypic variability [25]. Recent efforts have been made to analyze the genetic variability present in various countries, which may facilitate the characterization of species variability concerning both phenotypic and genotypic traits [9,26].

The evolutionary history of the *Citrus* genus, particularly *C. maxima* (pomelo), is complex and has been elucidated through various genomic studies. *Citrus* is believed to have originated in Southeast Asia millions of years ago, with C. maxima, along with *C. reticulata* and *C. medica*, identified as key progenitors of many cultivated *Citrus* species. Recent phylogenetic analyses have confirmed that these species represent distinct clades within the *Citrus* genus, highlighting their significance in the genetic makeup of modern *Citrus* varieties [27,28].

Research indicates that the cultivated *Citrus* species largely result from hybridization among these foundational progenitors. For instance, genomic analyses conducted by Wang *et al*. (2017) revealed that the evolution and domestication of *Citrus* crops are marked by significant changes in their reproductive systems, which have facilitated the emergence of diverse phenotypes [29]. Furthermore, the study by Wu *et al*. (2014) demonstrated that admixture events during *Citrus* domestication have contributed to the genetic diversity observed in various *Citrus* cultivars, particularly among mandarins and pomelos [30].

The genetic characterization of *C. maxima* has also been explored through the identification of specific gene families, such as the squamosa promoter binding protein (SBP) genes, which play crucial roles in flowering and fruit development [31,32]. These findings underscore the importance of understanding the molecular mechanisms underlying *Citrus* growth and development, particularly in relation to environmental factors such as fruit load.

Genomic work now shows that *C. maxima* (pomelo) – together with *C. reticulata* and *C. medica* – forms a distinct progenitor lineage underlying most cultivated *Citrus*, with domestication shaped by hybridization/admixture and shifts in reproductive systems [27-30]. Moving beyond origin narratives, these insights enable practice: phylogenomic assignments guide parent choice and marker-assisted introgression of desirable *C. maxima* alleles to improve fruit quality and size uniformity; functional evidence on SBP/SPL genes offers candidate markers for selection on flowering time and fruit-load responses [31,33]; and chloroplast comparative genomics identifies distinct cytotypes and divergent wild accessions that should be prioritized for *in situ*/*ex situ* conservation and core-collection assembly [28]. This applied framing links molecular findings directly to breeding and conservation strategies for commercially competitive, resilient pomelo.

Moreover, the phylogenetic relationships among *Citrus* species have been further clarified through comparative genomics, which has revealed the intricate connections between wild and domestic species. For example, Carbonell-Caballero *et al*. conducted a comprehensive analysis of chloroplast genomes, elucidating the evolutionary relationships among various *Citrus* species, including *C. maxima* [28]. This research not only contributes to our understanding of *Citrus* phylogeny but also provides insights into the genetic diversity that is essential for breeding programs aimed at enhancing *Citrus* cultivation.

2.2. Cultivation of Pomelo

Pomelo (*C. maxima*) is a fruit tree that exhibits remarkable adaptability to various soil types, ranging from sandy to heavy clay. However, its optimal growth is achieved in deep, medium-textured, fertile soils with a pH ranging from 5.5 to 6.5, which are typically found in lowland tropical regions [Table 2]. The ideal climatic conditions for pomelo cultivation include an annual rainfall of 150–180 cm and temperatures between 25°C and 32°C [34]. Research indicates that soil quality significantly influences pomelo productivity, with higher soil organic matter and nutrient availability correlating positively with yield [34].

Propagation techniques for pomelo are diverse, with air layering being the most common method in Southeast Asia, although grafting, budding, and stem cuttings are also employed. During the initial growth phase, consistent watering is crucial for establishing robust root systems. In the flowering stage, withholding irrigation until slight wilting occurs can stimulate flowering, while regular watering thereafter supports the development of new shoots, leaves, and fruits. Mature pomelo trees have substantial water requirements, with recommendations suggesting daily water needs of 100–250 L per tree during hot summer months [Table 2] [34]. Pruning is another essential practice in pomelo cultivation, as it shapes the tree and enhances light penetration and air circulation within the canopy. Initial pruning encourages horizontal branching, which improves fruit exposure and harvesting ease. Regular removal of dead or diseased branches, along with thinning overcrowded areas, promotes healthy growth and can enhance fruit quality.

Table 2: Pomelo cultivation data.

Aspect	Details
Soil requirements	Adaptable to sandy, loamy, and heavy clay soils; performs best in deep, fertile soils.
Optimal pH range	5.5–6.5
Rainfall requirements	150–180 cm annually
Temperature range	25°C–32°C
Propagation methods	Air layering (most common), grafting, budding, stem cutting, and seed propagation.
Irrigation practices	Frequent watering during establishment; reduced watering during flowering to induce blooms.
Pruning techniques	Initial pruning encourages horizontal branching; regular pruning improves light and air circulation.
Fertilization strategy	Annual application of 290 kg/ha nitrogen, 110 kg/ha phosphorus, 230 kg/ha potassium; adjusted based on growth stage.
Soil conservation	Practices like cover cropping and mulching to reduce leaching and enhance soil structure.
Special case study	Devanahalli pomelo in India: thrives in well-drained red soils with 300–800 mm annual rainfall, yields 300-400 fruits per tree annually.

Nutrient management is critical and should be tailored to the tree's developmental stage, soil characteristics, and climatic conditions. A balanced application of nitrogen (N), phosphorus (P), and potassium (K) is vital, with recommendations for mature trees suggesting approximately 290 kg/ha of nitrogen, 110 kg/ha of phosphorus (P_2O_5), and 230 kg/ha of potassium (K_2O) annually, divided into multiple applications throughout the growing season [Table 2] [35]. Maintaining soil fertility is fundamental for sustainable pomelo production, and practices such as cover cropping and mulching can mitigate nutrient leaching and enhance soil structure, positively influencing soil fertility and pomelo yields [45,58].

The Devanahalli pomelo, cultivated in the Bangalore Rural District of India, exemplifies the significance of region-specific cultivation practices. This variety thrives in well-drained red soils with annual rainfall between 300 and 800 mm, and its propagation methods include cuttings, grafts, and air layering, with each tree yielding an average of 300–400 fruits annually [26,34].

2.3. Productivity Concerns in Pomelo

Controlling flower induction in pomelo (*C. maxima*) is a critical challenge that significantly affects the productivity of this fruit. Various environmental factors, including temperature, water availability, nutrient levels, and light conditions, influence flowering induction [Table 3]. Among these, water stress has been identified as a pivotal factor that modulates the expression of the flowering locus T (FT) gene, which plays a crucial role in the flowering process [36]. They demonstrated that in the KKU-105 cultivar, flowering was induced under conditions of low nitrogen, with physiological metrics such as stomatal conductance and chlorophyll fluorescence, alongside an upregulation of *Citrus* FT mRNA levels. This indicates that the interaction between nutrient availability and water stress is vital for the regulation of flowering in pomelo.

To clarify which factors most strongly determine yield and quality in pomelo – and what requires local adaptation – we prioritize three levers: (i) potassium nutrition, (ii) water status around floral induction, and (iii) crop load/fruit presence. Adequate K is a universal driver of flowering and fruit set, with ~50% above baseline K markedly improving both [41]; however, the exact dose must be site-specific, guided by soil and leaf analyses. A brief, well-timed water deficit before induction can promote flowering through stress–hormone pathways [38,39], but intensity/duration must be tuned to climate, soil water-holding capacity, and rootstock vigor. On-tree fruit suppresses flowering gene expression and delays the next cycle, so timely harvest/thinning is broadly applicable, while load thresholds vary by canopy vigor and market size class [40]. Mechanistically, these practices converge on the FT/SOC1/LFY hubs and floral identity genes AP1/SEP [37,38], linking molecular control to practical management that improves flower initiation, fruit set, and size uniformity. The genetic basis for flowering induction in *Citrus* species is complex, involving multiple genes that interact under various environmental conditions. Key flowering genes such as FT, SOC1, and LFY are integral to the flowering process, with their expression levels being influenced by external stressors [37]. In addition, AP1 and SEP genes are crucial for floral meristem identity, further emphasizing the intricate regulatory networks that govern flowering in *Citrus*. The interplay between these genes and environmental factors such as water stress and temperature is essential for successful flower induction.

Research has shown that potassium fertilization can significantly enhance flowering and fruit set in pomelo. Bennici *et al*., reported that a 50% increase in the recommended potassium concentration resulted in a significant increase in flowering and fruit set rates, underscoring the importance of nutrient management in pomelo cultivation, particularly the role of potassium in promoting flowering [41].

Moreover, the effects of water-deficit stress and gibberellic acid on floral gene expression have been explored, revealing that these factors can regulate *Citrus* floral development through overlapping pathways [38]. For instance, the expression of AP1 and AP2 genes is necessary for bud determinacy and the downstream activation of floral identity genes, indicating a complex interaction between hormonal signals and environmental stressors. In addition, studies have shown that carbohydrate allocation during periods of water deficit can influence flowering, as seen in Meiwa kumquat trees, where water stress increased flower numbers [39].

The epigenetic regulation of flowering in *Citrus* is another area of interest [40] highlighted that the presence of fruit can inhibit the expression of flowering genes, thereby affecting the flowering cycle. This phenomenon illustrates the need for a comprehensive understanding of how fruit presence and environmental conditions interact to regulate flowering in pomelo.

2.4. Organic Amendments for Sustainable Production of Pomelo

Organic amendments are pivotal in enhancing the physical and chemical properties of soil, leading to significant increases in crop yield without compromising soil quality [Table 4] [42]. It emphasized that the application of organic materials can improve soil structure, water retention, and nutrient availability, which are essential for sustainable agricultural practices. The integration of organic amendments with inorganic fertilizers has been shown to yield positive results, but only when applied in optimal combinations tailored to specific crop needs and growth stages. This highlights the necessity of understanding the interactions between different types of fertilizers to maximize their effectiveness.

A critical phase in the life cycle of pomelo trees is during germination, where seed germination and subsequent growth are influenced by a myriad of biotic and abiotic factors. These factors vary significantly across species and are crucial for the healthy growth and survival of the plants. Despite farmers' best efforts, challenges persist regarding fruit quality, yield consistency, and fertilization costs. The effectiveness of organic fertilizers can be undermined if the quality of the fertilizer is not adequately assessed, or if the application does not consider the specific properties of the soil [43]. Therefore, a comprehensive understanding of soil characteristics and the scientific rationale behind fertilizer application is essential for optimizing pomelo cultivation.

Evidence supports organic amendments for soil function, but pomelo-specific guidance must highlight the key levers. Biochar and compost enhance microbial activity and nutrient cycling/availability, improve nutrient retention, and reduce leaching – thereby building soil organic matter and beneficial microbiota [34,44,46]. Direct pomelo evidence shows that potassium (K) fertilization can increase flowering and fruit set, while magnesium (Mg) status is critical for fruit quality [41,47]. Practically, adopt a biochar/compost base as a universal soil platform, then target K

Table 3: Factors influencing flower induction in pomelo.

Key factors	Details	Key findings
Environmental factors	Temperature, water stress, nutrients (low nitrogen), and light influence flowering; water stress modulates FT gene expression [36].	KKU-105 cultivar: Low nitrogen, stomatal conductance~50.53 m-2/S, chlorophyll fluorescence~0.30 Fv/Fm observed [36].
Genetic regulation	Key genes: FT, SOC1, LFY (flowering); AP1, SEP (floral meristem identity); interact with stressors like water and temperature [37].	Flowering is regulated by complex genetic networks sensitive to environmental cues [37].
Nutrient management	Potassium fertilizers (50% increase) significantly enhance flowering and fruit set [17].	Flowering increased by×4; fruit set 86–100%; yield increased×9 with potassium application [17].
Hormonal regulation	Water-deficit stress and gibberellic acid regulate floral gene expression, impacting AP1 and AP2 gene activity [38].	Carbohydrate allocation during water stress increases flowering in Meiwa kumquat trees [39].
Epigenetic regulation	Fruit presence inhibits flowering gene expression; epigenetic interactions affect the flowering cycle [40].	Comprehensive understanding needed of the fruit-presence impact on flowering cycles [40].

Table 4: Impacts of organic amendments and fertilization on pomelo cultivation.

Key aspects	Details	Key findings
Organic amendments	Enhance soil structure, water retention, and nutrient availability; improve sustainable practices [42].	Organic amendments improve soil physical and chemical properties significantly.
Integration of organic and inorganic fertilizers	Positive results when applied in optimal combinations tailored to crop needs and growth stages [42].	Effective only with scientific understanding of fertilizer-soil interactions.
Critical growth phase	Seed germination and growth influenced by biotic and abiotic factors; crucial for plant survival and healthy development.	Specific attention to the germination phase ensures higher survival rates and quality.
Challenges in fertilization	Challenges include fertilizer quality, soil property mismatches, and high fertilization costs [43].	Comprehensive soil analysis necessary for optimal fertilizer application.
Soil microbial activity	Biochar and compost improve soil fertility by enhancing nutrient cycling and microbial activity [44,45].	Biochar reduces nutrient leaching; compost increases soil organic matter and microbial health [46].
Specific nutrient role	Potassium improves flowering and fruit set; magnesium is critical for fruit quality [47].	Balanced fertilization improves fruit quality and yield in pomelo cultivation.

and Mg with site-specific rates derived from soil and leaf diagnostics (e.g., consider 50% above baseline K where tests show shortfall) to achieve sustainable growth, yield, and fruit quality [41,44,46-48].

2.5. Organic Fertilizers

The application of organic fertilizers and soil amendments plays a crucial role in enhancing soil physical, chemical, and biological properties, significantly improving pomelo growth and fruit quality. Table 5 summarizes key findings from various studies on the impact of organic and integrated nutrient management practices on pomelo cultivation. Pomelo-specific synthesis and recommendations. The strongest pomelo evidence points to: deep-placed organic fertilizer (16 kg/tree at 30–60 cm) improving fruit sugars (glucose, fructose, and sucrose), raising soil pH, organic matter and micronutrients, lowering bulk density, and enlarging root volume [49]; optimized integrated fertilization including Mg enhancing yield and fruit quality while reducing environmental burden [50]; and a balanced organic + mineral program (N 450, P 247.5, K 438, OM 2,250 kg/ha) improving leaf nutrient status, yield, and quality (Li *et al*., 2017). Supporting evidence shows cattle/chicken manures build humus and buffer acidity through H_2CO_3 interactions [51-53]; biochar/compost strengthen microbial activity and nutrient retention, curbing leaching [44,46,48]; amino-acid foliar (Vegeamino 3 Ml/L) supports mineral accumulation and vegetative growth in pomelo seedlings [54]; and organic + N strategies can sequester C while avoiding N_2O spikes in sandy loam [55]. Farmer takeaway: keep deep organic placement as the soil platform [49], combine organics (manure/compost/biochar) with mineral N–P–K per ratios, include Mg [50], consider amino-acid foliar 3 mL/L for early growth, and adjust rates by soil/leaf tests to hit yield and fruit-quality targets efficiently. In pomelo the use of cover cropping system, with dry leaves mulching, millet, faba bean, millet with faba bean, and manual weed control for a period of 120 days improved the microbial load in the soil along with arbuscular mycorrhizal fungi (AMF) colonization. Spraying of organic amino acid fertilizer has a positive effect on plant growth, and the same was observed when pomelo was sprayed with Vegeamino at 3 mL/L. The effect of organic amino acid fertilizer was observed in the accumulation of minerals in the leaves and vegetative growth of the seedlings [54]. The application of 16 kg of organic fertilizer at a depth of 30 and 60 cm had a positive effect on the concentration of glucose, fructose, and sucrose in the fruit, while chemical fertilizer helped in the quality and number of fruits. Increase in soil pH, micronutrient content, organic load, decreased soil bulk density and also increased the root volume when the soil was applied with organic fertilizer deep into the soil [49]. Riandana *et al.* observed that pomelo seedlings treated with chicken manure showed a positive effect on the shoot weight [53]. Magnesium is known to play a critical role in the plant growth and production of fruits, while magnesium plays a critical role in the growth, yield, and quality of fruits in pomelo. A trial to assess the effect of the in-place efficient integrated nutrient management, local farmer fertilization practices, optimum fertilization practice, and optimum fertilization practice with magnesium on pomelo was studies and it was observed that it could enhance yield, quality of fruit, and reduces the burden on the environment [50]. Li supplemented trees of pomelo combinations of organic and inorganic fertilizer and it was observed that treatment 2 (nitrogen 450 kg, phosphorus 247.5 kg, potassium 438 kg, and organic matter 2250 kg were used in per hectare) was able to improve nutrient content in leaves, fruit yield, and fruit quality, and it was found to be the best fertilization scheme for pomelo [56].

2.6. Biofertilizer

The application of beneficial microbes and agricultural residues plays a pivotal role in enhancing soil health, nutrient availability, and plant growth in pomelo cultivation. Table 6 highlights key findings from studies on the impact of microbial formulations and residue management practices on seedling growth, root development, and soil nutrient enrichment. Evidence converges on two effective axes for pomelo: (i) nursery/early-stage microbial consortia and (ii) orchard residue–nutrient integration. In containers, *Azospirillum* + phosphorus-solubilizing bacteria (PSB) + vesicular arbuscular mycorrhizae (VAM)/AMF improved seedling height, girth, leaf number/area, and biomass; adding *Pseudomonas fluorescens* further increased root weight, primary/secondary roots, and root volume at 120 days [58]. Residue programs also showed benefits: mushroom residue + optimized NPK + lime enhanced root length/surface area and raised soil pH and nutrients [59]; rice straw residue + *Bacillus subtilis*/*Azotobacter*/*Azospirillum* increased leaf N and K in grafted pomelo seedlings [60]. These align with mechanisms whereby inoculants fix/solubilize N–P–K, release growth promoters/antagonists, and rebuild microflora [61,62]. Application of *Azospirillum* spp. PSB and VAM to pomelo potting mixture containing sand, soil, and farm yard manure (2:1:1) in polythene bags had beneficial effect on the height of the seedling, seedling girth, number of leaves, leaf area, and weight of the seeds, while the addition of *Azospirillum, Phosphate solubilizing bacteria* and *P. fluorescens* and VAM had better root weight, number of primary and secondary roots, root length, and volume of root at the end of 120 days [58]. Residue obtained after mushroom harvest is known to improve the soil structure by adding N, P, K, Ca, and Mg

Table 5: Effects of organic fertilizers and soil amendments on pomelo.

Aspect	Details	References
Impact of cattle manure	Improves soil humus content, decreases acidity; reacts with soil adsorption complex to reduce acidity [51,52].	[51,52]
Effects on sandy loam soil	Long-term organic manure reduces N_2O emissions, sequesters atmospheric C, and maintains applied N [55]	[55]
Cover cropping and mulching	Improves microbial load and arbuscular mycorrhizal fungi colonization using cover crops and dry leaf mulching (120 days).	[44]
Amino acid fertilizer	Spraying Vegeamino at 3 mL/L improves plant growth, mineral accumulation in leaves, and vegetative growth [54].	[54]
Deep application of organic fertilizer	Application of 16 kg organic fertilizer at 30–60 cm depth increases glucose, fructose, sucrose in fruit, improves soil pH, micronutrients, and root volume [49].	[53]
Use of chicken manure	Chicken manure positively affects shoot weight in pomelo seedlings [53].	[53]
Role of magnesium	Critical for plant growth and fruit quality; enhances yield and quality when integrated with optimum practices [57].	[57]
Integrated nutrient management	Combines organic and inorganic fertilizers to enhance yield, quality, and environmental sustainability [57]	[57]
Optimal fertilization scheme	Optimal scheme: Nitrogen 450 kg, phosphorus 247.5 kg, potassium 438 kg, organic matter 2250 kg/ha [57]	[57]

Table 6: Effects of microbial and residue applications on pomelo cultivation.

Aspect	Details	References
Beneficial microbes application	Improves soil health by mobilizing nutrients, fixing NPK, releasing growth promoters, and degrading organic matter [61].	[61]
Soil nutrient enrichment	Enriches soil micro and macro-nutrients; fixes nitrogen, solubilizes phosphate and potassium; releases plant growth promoters and antibiotics [61].	[61]
Impact on seedling growth	*Azospirillum*, phosphorus solubilizing bacteria, and VAM improve height, girth, number of leaves, and leaf area of pomelo seedlings [61].	[61]
Root development	Combination of beneficial microbes improves root weight, primary and secondary root numbers, length, and volume after 120 days [61].	[61]
Mushroom residue application	Mushroom residue enhances soil structure, increases N, P, K, Ca, Mg levels, and raises soil pH; improves root length and surface area [64].	[64]
Rice straw residue application	Rice straw with *Bacillus subtilis*, *Azotobacter*, and *Azospirillum* increases leaf nitrogen and potassium; enhances soil nitrogen with organic fertilizer [60].	[60]

to the soil and has an influence on increasing soil pH. The addition of mushroom residue, in combination with optimization NPK fertilizer and lime, had a positive effect on the root length and root surface area [63]. Application of rice straw residue along with *B. subtilis*, *Azotobacter chroococcus*, and *Azospirillum brasilense* to pomelo seedling grafted onto two different Citrus rootstocks (Fulcamaryana and Bitter orange) had superior content of leaf nitrogen. Increased potassium accumulation in leaves was observed when treated with *Azospirillium* and *Bacillus*, while soil nitrogen was higher when treated with *Azospirillum* and Azotobacter in combination with organic fertilizer [60].

2.7. Arbuscular Mycorrhiza (AM)

AM fungi form symbioses with many terrestrial plants, including *Citrus*, enhancing nutrient uptake, stress tolerance (biotic/abiotic), and fruit quality [65,66]. By releasing metabolites, glomalin-like proteins, and glycoproteins, AMF improves soil fertility and physical–chemical traits, reinforcing tolerance to stresses [67]. At least, 45 species (7 genera) inhabit the *Citrus rhizosphere* [67]. *Citrus* is highly AMF-dependent because of short and sparse root hairs; phosphorus (P) deficiency particularly depresses growth and stress resistance, making AMF-mediated P acquisition critical [68]. In pomelo, AMF plus biofertilizer consortia improved seed germination and seedling growth relative to biofertilizers alone [58]. Seedlings inoculated with *Gigaspora margarita*, *Glomus mosseae*, and *Glomus versiforme* accumulated more N, P, K, Ca, Mg, Zn, Cu, and Mn; notably, *G. mosseae* alone gave stronger vegetative growth [69]. AMF inoculation also mitigated the typical consequences of P shortage – lower nutrient assimilation, reactive oxygen species overproduction, reduced photosynthesis – and thereby protected fruit quality [68,70]. Field observations indicate seasonal dynamics: Pomelo roots showed ~76% AM colonization with interannual variation [71], and colonization peaked in summer, then autumn, spring, and winter; arbuscule/vesicle/spore percentages also varied, with highest infection in summer and maximum spore density in autumn [71]. Practically, these patterns suggest timing inoculation/booster applications before early summer, maintaining moisture and organic cover to support colonization, and reducing readily available P around peak colonization to avoid suppressing symbiosis – while monitoring leaf P to prevent deficiency [68,72]. Reports from Vietnam also note an ectomycorrhizal association of *Phlebopus spongiosus* with pomelo roots (non-saprophytic), though its agronomic value requires further field comparison before recommendation at scale [73].

2.8. Compost

Table 7 illustrates that the application of compost and biochar can lead to improvements in soil pH, organic matter content, bulk density, and exchangeable cations, which are associated with increased pomelo yields. In this context, compost functions primarily as a nutrient- and microbe-rich organic input: Aerobic decomposition produces humic substances that improve nutrient retention and water-holding capacity and enhance biological activity [48,74,75]. Effects are typically strong but medium-lived, reflecting ongoing mineralization and turnover of organic matter. By contrast, biochar acts mainly as a structural and chemical conditioner – increasing pH, cation retention, and

Table 7: Impact of compost and biochar amendments on soil properties and pomelo yield.

Parameter	Control	Compost treatment	Biochar treatment
Soil pH	4.5	5.5	5.8
Soil organic matter (%)	2.0	3.5	3.8
Bulk density (g/cm^3)	1.40	1.25	1.20
Exchangeable cations (cmol/kg)	5.0	7.5	8.0
Pomelo yield (tons/ha)	10	15	16

porosity and reducing leaching, with more persistent changes due to its recalcitrant carbon matrix [48,76]. In acidic pomelo soils, studies report that both inputs raise pH and organic matter, lower bulk density, and increase exchangeable cations, with yield gains consistent with these shifts [76]. Practically, co-application leverages compost's short-to-medium-term nutrient/microbial boost and biochar's longer-term buffering/retention, but orchard-scale durability (rates, intervals) for pomelo remains to be defined. We, therefore, highlight the need for long-term field trials in pomelo orchards to calibrate site-specific application rates and re-application intervals, using routine monitoring of soil pH, organic matter, bulk density, exchangeable cations, and yield to guide adjustments [48,74-76]. The presence of a wide variety of microorganisms in compost not only aids in the breakdown of organic matter but also fosters interactions that can improve nutrient availability for plants. This microbial diversity is crucial, as it helps to create a balanced soil ecosystem capable of withstanding environmental stresses and promoting sustainable agricultural practices. Furthermore, the improved soil structure and fertility resulting from compost amendments facilitate better root development and plant growth. Enhanced soil aeration and water infiltration, resulting from the addition of compost, allow for deeper root penetration and more efficient nutrient uptake. This is particularly important in agricultural systems where soil compaction can limit root growth and water movement, ultimately affecting crop yields.

2.9. Vermicomposting

Table 8 highlights the multifaceted benefits of vermicompost – often referred to as "black gold" – in enhancing soil health, promoting plant growth, and contributing to sustainable agricultural practices. Vermicompost is a microbially active, nutrient-dense amendment whose fine worm casts concentrate N, P, and K, stimulate germination and early growth, and contribute beneficial microbes, growth promoters, pathogen suppression, and heavy-metal detoxification [77-80]. While these benefits are well documented across crops, pomelo-specific orchard evidence remains limited. To date, few studies have examined vermicompost's role in strengthening pomelo's resistance to major diseases such as Huanglongbing (HLB) – a systemic bacterial infection caused by *Candidatus Liberibacter asiaticus* transmitted by psyllids. Although vermicompost does not directly eliminate HLB pathogens, its consistent application can enhance plant vigor, stimulate induce systemic resistance (ISR), and improve root-zone microbiome diversity, indirectly reducing HLB severity and secondary infections. Increased microbial antagonists and improved nutrient balance (particularly calcium, zinc, and manganese) have been correlated with reduced symptom expression in *Citrus* affected by HLB [81-83]. As an interim, the pomelo-oriented nutrient and disease management program should integrate vermicompost application during the nursery and establishment phases, and in bearing orchards, apply it in bands around the dripline timed to post-harvest recovery or pre-flowering. Integration with compost or biochar further stabilizes moisture and enhances cation retention, creating favorable conditions for beneficial microbial populations that help suppress root and vascular pathogens, potentially mitigating HLB progression. Regular soil and leaf diagnostics are essential to refine application rates and nutrient balance, especially under HLB stress conditions. To set sustainable doses, intervals, and evaluate disease-mitigation effects, multi-season orchard trials should compare vermicompost alone versus combinations with organic and mineral inputs, while monitoring yield, fruit quality, nutrient-release dynamics, and HLB symptom development over fruiting cycles [77-80].

Despite clear, cross-crop benefits of vermicompost, pomelo-specific evidence on growth and yield remains scarce; nonetheless, because pomelo performs best on well-drained, nutrient-rich soils, vermicompost is a strong candidate to enhance fertility and plant vigor while improving soil structure and biology – boosting aeration, water retention, microbial diversity, and disease suppression [78,81,82,84]. Mechanistically, vermicompost raises soil organic C, increases nutrient availability, and stimulates beneficial microbiota, supporting productivity and recycling organic wastes while reducing reliance on synthetic fertilizers [85,86]. Practically for pomelo, use vermicompost in the nursery/establishment phase and, in bearing orchards, band around the dripline, timed to post-harvest recovery or pre-flowering, integrate with existing compost/biochar programs to stabilize moisture and cation retention, and adjust rates by soil and leaf diagnostics. To set sustainable application rates and intervals and to quantify synergies with organic/inorganic inputs, prioritize multi-season, orchard-scale trials that track yield, fruit quality, and nutrient-release dynamics across fruiting cycles.

2.10. Biopesticides

Bio-derived and mineral agents can suppress pomelo pests and diseases while minimizing ecosystem harm and fit well within an integrated pest management (IPM) framework [87]. In comparative field terms, predatory mites – *Amblyseius barkeri*, *Amblyseius cucumeris*, *Amblyseius orientalis* – consistently provide the strongest, most durable suppression of *Frankliniella occidentalis* and *Panonychus citri*; in pomelo orchards, control reached 98.1% at 120 days, with *A. barkeri* establishing persistent populations that kept *P. citri* below economic thresholds and, when deployed at scale in China, reduced control costs, and improved fruit quality [22,88]. Botanicals and wood vinegar (e.g., *Stemona tuberosa*, *Tinospora crispa*, and *Derris elliptica*) deliver targeted suppression of thrips and *Citrus* leaf miner and can enhance peel thickness, firmness, and °Brix (thicker peel with Tinospora; improved firmness/°Brix with Stemona), making them valuable for hot spots and pre-harvest windows given short PHI/MRL; however, their short residuals typically require re-treatment after rain or high ultraviolet (UV), so cost/ha depends on application frequency [89]. Microbial/antagonistic agents also contribute: Community biopesticides reduced *Botryodiplodia theobromae* stem-rot severity by 16.2% with visible wound healing and new shoots [90]; *Chaetomium* metabolites suppressed *Phytophthora palmivora* [91]; and a PNTS 06-05 bacterial extract inhibited 95.56% mycelial growth of *Phytophthora parasitica in vitro* (fosetyl-Al = 100%), with promising but lower field efficacy – best positioned in rotation, not as a stand-alone replacement [92,93]. For economic feasibility and operational compatibility, a pragmatic IPM sequence is to (1) anchor with mineral tools – notably kaolin particle films – through vegetative flushes and pre-bloom to deter vector landing, reduce sunburn and blemish, and provide a low-cost, field-robust layer with short REI/PHI and low MRL; (2) rotate

Table 8: Properties and benefits of vermicompost in agriculture.

Property/Benefit	Description
Nutrient-rich composition	Vermicompost is rich in essential plant nutrients, including nitrogen (N), phosphorus (P), potassium (K), and micronutrients, providing a balanced nutrient supply for crops.
Enhanced soil structure	Improves soil aeration, porosity, and water-holding capacity, leading to better root development and plant growth.
Increased microbial activity	Contains beneficial microorganisms that promote nutrient cycling, suppress soil-borne pathogens, and enhance soil fertility.
Growth-promoting substances	Enriched with plant growth regulators such as auxins and cytokinins, which stimulate seed germination and plant development.
Heavy metal detoxification	Reduces the bioavailability of heavy metals in soil, thereby decreasing their uptake by plants and mitigating toxicity.
Disease suppression	Possesses properties that inhibit pathogenic microbes, reducing the incidence of plant diseases and minimizing the need for chemical pesticides.
Environmental sustainability	Converts organic waste into valuable fertilizer, reducing landfill use and promoting sustainable waste management practices.

microbial agents at susceptible pest/disease stages under favorable microclimates (evening/overcast for fungi; avoid high UV), avoiding tank mixes with broad-spectrum pesticides that reduce microbial viability; and (3) deploy botanical spot sprays on edge rows/hot spots and near harvest. Pair this with soil pH correction and drainage improvement on acidic clays to curb *Phytophthora* risk. Monitor with traps, flush scouting, and fruit inspections; act at defined thresholds; rotate modes of action; preserve beneficials; track PHI/MRL for export compliance; and log cost per controlled hectare to refine mixes and timing annually. This comparative, economics-aware, and IPM-integrated approach improves field reliability, manages costs, and aligns with existing pomelo orchard practice using the cited tools and evidence [22,69,87-89,91-93]. Fungal antagonistic bacterial extract from PNTS 06-05 was able to inhibit 95.56% mycelial growth of *P. parasitica*, while fosetyl-aluminum did its best at 100% growth inhibition. The field trial showed promising results of PNTS 06-05, even though the efficiency was lower. The use of natural antagonistic extract for a plant disease will be an added advantage for the soil fertility.

2.11. Benefits of Organic Amendments to Soil

The rapid expansion of niche markets – alongside price volatility and tougher competition – has pushed farmers toward quicker, simpler routes to better outcomes [94], and for pomelo (*C. grandis*), the case for organic is compelling because consumer-health and environmental gains align with the fruit's therapeutic profile (Vitamin C, folates, carotenoids, limonoids, and diverse phytochemicals) and are maximized when synthetic inputs and off-target contaminants are minimized [95-97]. To convert that rationale into practice for pomelo, growers can rely on field-ready organic inputs: Apply compost and/or vermicompost around the dripline post-harvest and pre-flowering to build soil organic C, water holding, cation exchange, and beneficial microbiota; co-apply biochar with organics to stabilize pH, enhance nutrient retention, and reduce leaching; inoculate at nursery/planting with beneficial consortia (AMF, N-fixers, and P-solubilizers) to strengthen roots and N–P capture; and run a low-residue protection program that prioritizes kaolin particle films through flushes and pre-bloom, then rotates microbial antagonists and botanicals at defined thresholds within an IPM calendar. Close the loop each season with soil tests (pH, organic matter, and exchangeable cations) and mid-season leaf diagnostics to tune rates and timings. Transitional hurdles are real but manageable: Certification costs and compliance can be contained by starting with pilot blocks, setting buffer zones, and keeping simple input logs; yield variability during conversion can be cushioned by front-loading soil organic matter inputs (compost/vermicompost + biochar), maintaining balanced mineral nutrition within organic rules, and emphasizing preventive IPM (sanitation, canopy airflow, and kaolin); and input access improves through on-farm composting, cooperative purchasing, and supplier agreements, complemented by training on material maturity, moisture, and timing. As consumer awareness and willingness-to-pay rise and organic price premiums are documented [98], a phased conversion – sequencing higher-value blocks first and guiding decisions with soil/leaf diagnostics – balances opportunity with risk even where inputs remain scarce or costly [99]. In short, linking consumer health, environmental sustainability, and pomelo's therapeutic value to specific, workable inputs – compost/vermicompost, biochar co-application, microbial inoculation at establishment, and low-residue IPM – makes organic pomelo operational and investable while addressing certification costs, yield variability, and input access up front [94-97,99,100].

Organic disease management in pomelo offers a sustainable pathway to mitigate key threats such as HLB and soil-borne pathogens (*Phytophthora*, *Fusarium*, and *Colletotrichum*). The integration of vermicompost, compost, and biochar improves soil structure, organic carbon, and microbial activity, fostering a rhizosphere that suppresses pathogen populations and enhances plant immunity. In particular, vermicompost supplies beneficial microbes, including *Bacillus, Pseudomonas*, and *Trichoderma*, that are capable of inducing systemic resistance (ISR) and reducing the severity of HLB symptom expression. Co-application with biochar stabilizes pH, improves nutrient retention, and provides a microhabitat for antagonistic organisms active against both root and vascular pathogens. At the establishment stage, microbial inoculants – including AMF, N-fixers, and P-solubilizers – enhance micronutrient availability (especially Zn, Mn, and Ca) linked to HLB tolerance. On the canopy level, kaolin films, botanical extracts (neem, *Citrus* oil), and microbial biocontrols (*Beauveria* and *Metarhizium*) can deter psyllid vectors and reduce foliar disease incidence within an organic IPM framework. Regular soil and leaf diagnostics enable adaptive management of nutrient and biological inputs, maintaining a balanced system under organic rules. Over time, these synergistic organic practices strengthen pomelo resilience, stabilize yields, and reduce dependence on synthetic pesticides, aligning plant health, disease control, and sustainability goals [101,102].

2.12. Climate Variability and Adaptation in Organic Pomelo Systems

Climate variability – through irregular rainfall, rising temperatures, and drought – directly affects pomelo growth, flowering, and disease dynamics. Organic practices such as vermicompost, compost, and biochar application enhance soil carbon, water retention, and microbial balance, helping trees tolerate stress and recover faster. Microbial inoculants (AMF, N-fixers, and P-solubilizers) further improve nutrient efficiency under fluctuating conditions. Together, these inputs make organic pomelo systems inherently more climate-resilient and adaptive. Integrating such soil-focused strategies ensures sustainable yield stability under changing climatic patterns [101,102].

3. CONCLUSION

Organic amendments plausibly improve soil function, reduce synthetic inputs, and support fruit quality in pomelo, but the decisive evidence remains crop-specific and long-term. Most reported benefits are generalized from other systems; therefore, orchard-scale, multi-season trials in pomelo – quantifying yield, marketable grade, °Brix/TA, firmness, defect rates, soil health, and farm-level returns – are essential to move from promise to proof.

Translating benefits into practical strategies for pomelo growers, current best-bet inputs are as follows: (i) Compost/vermicompost banded post-harvest and pre-flowering to build organic C and biological activity; (ii) biochar co-applied with organics to stabilize pH and nutrient retention; (iii) beneficial microbes (AMF and compatible N-fixers/P-solubilizers) targeted to nursery and planting to strengthen rooting and N–P uptake; and (iv) low-residue IPM centered on kaolin particle films (through flushes and pre-bloom) with microbial/botanical rotations at thresholds to protect fruit quality while preserving beneficials. These practices should be tuned by routine soil tests and leaf diagnostics to set rates and timings under local conditions.

Adoption will hinge on managing transitional challenges. To address certification costs, start with pilot blocks, establish buffer zones, and maintain simple input logs while securing buyers for expected premiums. To mitigate yield variability during conversion, front-load soil organic matter inputs (compost/vermicompost + biochar), keep mineral nutrition balanced within organic standards, and emphasize preventive IPM. To improve access to inputs, develop on-farm composting where feasible, pool demand through cooperatives, and secure reliable suppliers. With this crop-specific research agenda and a phased, risk-aware adoption pathway, organic pomelo can become both environmentally sound and operationally and economically credible for growers.

4. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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This study does not involve experiments on animals or human subjects and, therefore, did not require ethical approval.

8. DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author on reasonable request.

9. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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