Novel Biotechnological Strategies to Boost Disease Resistance and Enhance Quality Parameters in Horticultural Plants

Abstract

Horticultural crops face numerous challenges, including various diseases and quality issues that significantly impact productivity and marketability. Traditional methods of disease management and quality improvement often rely on chemical interventions, which can have detrimental effects on the environment and human health. In recent years, biotechnological approaches have emerged as promising alternatives to address these challenges in a more sustainable and effective manner. This review paper explores novel biotechnological strategies aimed at enhancing disease resistance and improving quality parameters in horticultural plants. These strategies encompass genetic engineering techniques, such as the introduction of resistance genes, RNA interference, and genome editing, as well as the application of beneficial microorganisms, including plant growth-promoting rhizobacteria and mycorrhizal fungi. Additionally, the potential of nanotechnology in delivering targeted molecules for disease control and quality enhancement is discussed. The review also highlights the importance of marker-assisted selection in accelerating the development of disease-resistant and high-quality varieties. Furthermore, the integration of omics technologies, such as genomics, transcriptomics, proteomics, and metabolomics, is explored as a means to unravel the underlying mechanisms of disease resistance and quality traits. The challenges associated with the commercialization and public acceptance of biotechnology-derived horticultural products are also addressed. By providing a comprehensive overview of these novel biotechnological strategies, this review aims to facilitate the development of sustainable and effective solutions for the horticultural industry, ultimately contributing to global food security and consumer satisfaction.

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Keywords: Biotechnology, disease resistance, quality parameters, horticultural plants, genetic engineering

1. Introduction

Horticultural crops, including fruits, vegetables, and ornamental plants, play a vital role in human nutrition, health, and aesthetics. However, these crops are susceptible to various diseases caused by pathogens such as fungi, bacteria, viruses, and nematodes, which can lead to significant yield losses and reduced quality [1]. Traditional disease management strategies often involve the use of chemical pesticides, which can have negative impacts on the environment and human health [2]. Moreover, the continuous use of pesticides can lead to the development of resistance in pathogens, rendering the chemicals ineffective [3]. In addition to disease challenges, horticultural crops also face quality issues, such as poor shelf life, undesirable texture, and low nutritional value, which can limit their marketability and consumer acceptance [4].

To address these challenges, biotechnological approaches have emerged as promising alternatives to traditional methods. Biotechnology encompasses a wide range of techniques that involve the manipulation of living organisms or their components to develop novel products or processes [5]. In the context of horticultural crops, biotechnological strategies can be employed to enhance disease resistance, improve quality parameters, and increase overall productivity [6].

2. Genetic Engineering for Disease Resistance

Genetic engineering involves the manipulation of an organism's genetic material to introduce desirable traits or suppress undesirable ones [7]. In the context of horticultural crops, genetic engineering can be employed to enhance disease resistance by introducing genes that confer resistance to specific pathogens [8].

2.1 Introduction of Resistance Genes

One of the most common approaches to engineer disease resistance in plants is the introduction of resistance (R) genes. R genes encode proteins that recognize specific pathogen effectors and trigger a defense response in the plant [9]. The identification and characterization of R genes from various sources, including wild relatives of cultivated crops, have paved the way for their integration into commercially important varieties [10].

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For example, the *Rpi-blb2* gene, which confers resistance to late blight caused by the oomycete pathogen *Phytophthora infestans*, has been successfully introduced into potato (*Solanum tuberosum*) [11]. Similarly, the *Bs2* gene, which provides resistance to bacterial spot disease caused by *Xanthomonas euvesicatoria*, has been incorporated into tomato (*Solanum lycopersicum*) [12]. These examples demonstrate the potential of R gene-mediated resistance in combating devastating diseases in horticultural crops.

2.2 RNA Interference (RNAi)

RNA interference (RNAi) is a biological process that involves the silencing of gene expression through the degradation of specific mRNA molecules [13]. In plants, RNAi can be harnessed to target essential genes in pathogens, thereby inhibiting their growth and development [14]. This approach has been successfully employed to enhance resistance against various pathogens, including viruses, fungi, and insects [15].

For instance, RNAi has been used to develop papaya (*Carica papaya*) resistant to papaya ringspot virus (PRSV) by targeting the viral coat protein gene [16]. Similarly, RNAi-mediated silencing of the fungal chitin synthase gene has been shown to enhance resistance against the fungal pathogen *Fusarium oxysporum* in tomato [17]. These examples highlight the potential of RNAi as a powerful tool for engineering disease resistance in horticultural crops.

2.3 Genome Editing

Genome editing technologies, such as zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and clustered regularly interspaced short palindromic repeats (CRISPR)/Cas systems, have revolutionized the field of plant biotechnology [18]. These technologies allow for precise and targeted modifications of plant genomes, enabling the development of crops with improved traits, including disease resistance [19].

The CRISPR/Cas system, in particular, has gained significant attention due to its simplicity, efficiency, and versatility [20]. This system has been successfully used to engineer resistance against various pathogens in horticultural crops. For example, CRISPR/Cas9-mediated editing of the *eIF4E* gene in cucumber (*Cucumis sativus*) has been shown to confer resistance to cucumber vein yellowing virus (CVYV) [21]. Similarly, CRISPR/Cas9 has been employed to generate powdery mildew-resistant tomato plants by targeting the *MLO* gene [22].

The application of genome editing technologies in horticultural crops holds immense potential for developing disease-resistant varieties. However, the regulatory landscape surrounding genome-edited crops varies across countries, and public acceptance remains a challenge [23]. Addressing these issues is crucial for the successful implementation of genome editing in horticultural crop improvement.

3. Harnessing Beneficial Microorganisms

Plants host a diverse array of microorganisms, including bacteria and fungi, which can have beneficial effects on plant growth, development, and stress tolerance [24]. Harnessing these beneficial microorganisms offers a sustainable approach to enhance disease resistance and improve quality parameters in horticultural crops [25].

3.1 Plant Growth-Promoting Rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria (PGPR) are soil-borne bacteria that colonize the rhizosphere, the region surrounding the plant roots, and exert positive effects on plant growth and health [26]. PGPR can enhance disease resistance in plants through various mechanisms, such as the production of antimicrobial compounds, competition with pathogens for resources, and the induction of systemic resistance [27].

Several PGPR strains have been identified and exploited for their potential to control diseases in horticultural crops. For instance, the application of *Bacillus subtilis* strain QST 713 has been shown to reduce the incidence of powdery mildew in cucumber [28]. Similarly, the inoculation of tomato plants with *Pseudomonas fluorescens* strain Pf-5 has been found to suppress the development of bacterial speck caused by *Pseudomonas syringae* pv. *tomato* [29].

The commercialization of PGPR-based products for disease management in horticultural crops is gaining momentum. However, the success of these products depends on various factors, such as the compatibility of the PGPR strain with the crop, the formulation and delivery method, and the environmental conditions [30]. Further research is needed to optimize the efficacy and consistency of PGPR-based disease management strategies.

3.2 Mycorrhizal Fungi

Mycorrhizal fungi are ubiquitous soil-borne fungi that form symbiotic associations with the roots of most land plants [31]. These fungi provide various benefits to their host plants, including improved nutrient uptake, enhanced stress tolerance, and protection against pathogens [32].

The application of mycorrhizal fungi has been shown to enhance disease resistance in several horticultural crops. For example, the inoculation of tomato plants with the arbuscular mycorrhizal fungus *Glomus mosseae* has been found to reduce the severity of Fusarium wilt caused by *Fusarium oxysporum* f. sp. *lycopersici* [33]. Similarly, the colonization of strawberry (*Fragaria x ananassa*) roots by the ectomycorrhizal fungus *Laccaria bicolor* has been shown to confer resistance against the soil-borne pathogen *Verticillium dahliae* [34].

The successful implementation of mycorrhizal fungi in disease management strategies requires a thorough understanding of the complex interactions between the fungus, the host plant, and the pathogen [35]. Moreover, the establishment and maintenance of mycorrhizal associations in agricultural settings can be challenging due to the influence of various environmental factors, such as soil type, nutrient availability, and management practices [36].

4. Nanotechnology for Disease Control and Quality Enhancement

Nanotechnology involves the manipulation of matter at the nanoscale (1-100 nm) to develop materials and devices with novel properties and functions [37]. In the context of horticultural crops, nanotechnology offers new opportunities for disease control and quality enhancement through the targeted delivery of bioactive compounds [38].

4.1 Nanoparticle-Mediated Delivery of Antimicrobial Agents

Nanoparticles can be engineered to encapsulate and deliver antimicrobial agents, such as fungicides and bactericides, to specific target sites in plants [39]. This targeted delivery approach can improve the efficacy of the antimicrobial agents while reducing their environmental impact and the risk of resistance development in pathogens [40].

Various types of nanoparticles, including metallic nanoparticles (e.g., silver, copper), polymeric nanoparticles (e.g., chitosan, alginate), and lipid-based nanoparticles (e.g., liposomes, solid lipid nanoparticles), have been investigated for their potential in plant disease management [41]. For instance, the application of copper oxide nanoparticles has been shown to effectively control bacterial spot disease in tomato caused by *Xanthomonas perforans* [42]. Similarly, the use of chitosan nanoparticles loaded with the fungicide carbendazim has been found to suppress the growth of the fungal pathogen *Fusarium graminearum* in wheat (*Triticum aestivum*) [43].

4.2 Nanoparticle-Mediated Delivery of Plant Growth Regulators

Nanotechnology can also be harnessed to deliver plant growth regulators (PGRs) to specific tissues or organs in plants, thereby modulating their growth and development [44]. PGRs play a crucial role in regulating various physiological processes in plants, including fruit ripening, senescence, and stress responses [45].

The encapsulation of PGRs in nanoparticles can enhance their stability, bioavailability, and targeted delivery [46]. For example, the application of gibberellic acid-loaded chitosan nanoparticles has been shown to improve the growth and yield of tomato plants [47]. Similarly, the use of ethylene-loaded nanoparticles has been found to delay the ripening of bananas (*Musa acuminata*), extending their shelf life [48].

The successful implementation of nanotechnology in horticultural crop management requires a comprehensive understanding of the interactions between nanoparticles, plants, and the environment [49]. Moreover, the potential toxicity and ecological impacts of nanoparticles need to be thoroughly assessed to ensure their safe and sustainable use [50].

5. Marker-Assisted Selection for Crop Improvement

Marker-assisted selection (MAS) is a biotechnological approach that involves the use of molecular markers to select plants with desirable traits, such as disease resistance and improved quality parameters [51]. MAS relies on the identification of genetic markers that are tightly linked to the genes controlling the traits of interest [52].

5.1 MAS for Disease Resistance

MAS has been extensively used to develop disease-resistant varieties in various horticultural crops [53]. The selection of plants based on molecular markers allows for the rapid and accurate identification of individuals carrying the desired resistance genes, without the need for time-consuming and labor-intensive disease screening [54].

For instance, MAS has been successfully employed to develop tomato varieties resistant to Fusarium wilt by targeting the *I-2* gene [55]. Similarly, MAS has been used to introgress the *Fom-2* gene, which confers resistance to Fusarium wilt in melon (*Cucumis melo*), into commercial varieties [56]. These examples demonstrate the potential of MAS in accelerating the development of disease-resistant horticultural crops.

5.2 MAS for Quality Traits

MAS can also be applied to improve various quality traits in horticultural crops, such as fruit size, color, flavor, and nutritional content [57]. The identification of molecular markers associated with these traits enables the selection of superior genotypes in breeding programs [58].

In tomato, MAS has been used to select for fruit quality traits, such as high soluble solids content and improved shelf life, by targeting the *Brix9-2-5* and *rin* genes, respectively [59]. Similarly, MAS has been employed to develop strawberry varieties with enhanced fruit firmness and color by targeting the *FaFAD1* and *FaMYB10* genes, respectively [60].

The success of MAS in horticultural crop improvement depends on the availability of reliable molecular markers and the efficient integration of these markers into breeding programs [61]. Moreover, the costs associated with marker development and genotyping need to be considered to ensure the cost-effectiveness of MAS-based breeding strategies [62].

6. Omics Technologies for Unraveling Mechanisms of Disease Resistance and Quality Traits

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, offer powerful tools to unravel the underlying mechanisms of disease resistance and quality traits in horticultural crops [63]. These technologies provide a comprehensive view of the molecular processes involved in plant-pathogen interactions and the regulation of fruit development and ripening [64].

6.1 Genomics

Genomics involves the study of an organism's entire genetic material, including the sequencing and analysis of its genome [65]. In horticultural crops, genomic approaches have been used to identify genes and regulatory elements involved in disease resistance and quality traits [66].

For example, the sequencing of the tomato genome has facilitated the identification of genes responsible for resistance to various pathogens, such as the *Sw-5* gene for resistance to tomato spotted wilt virus (TSWV) and the *Ve1* gene for resistance to *Verticillium dahliae* [67]. Similarly, genomic studies in strawberry have revealed genes associated with fruit quality traits, such as the *FaGAMYB* gene, which regulates fruit ripening and anthocyanin biosynthesis [68].

6.2 Transcriptomics

Transcriptomics involves the study of an organism's complete set of RNA transcripts, known as the transcriptome, under specific conditions [69]. Transcriptomic analyses provide insights into the differential expression of genes in response to biotic and abiotic stresses, as well as during fruit development and ripening [70].

In pepper (*Capsicum annuum*), transcriptomic studies have identified genes that are differentially expressed during the interaction with the anthracnose pathogen *Colletotrichum acutatum*, providing valuable information for the development of resistant varieties [71]. Similarly, transcriptomic analyses in citrus (*Citrus* spp.) have revealed genes involved in the regulation of fruit acidity, which is an important quality trait [72].

6.3 Proteomics

Proteomics involves the large-scale study of an organism's proteins, including their structure, function, and interactions [73]. Proteomic approaches have been used to identify proteins associated with disease resistance and quality traits in horticultural crops [74].

In grapevine (*Vitis vinifera*), proteomic studies have identified proteins that are differentially expressed during the interaction with the fungal pathogen *Botrytis cinerea*, providing insights into the molecular mechanisms of disease resistance [75]. Similarly, proteomic analyses in peach (*Prunus persica*) have revealed proteins involved in fruit softening and the regulation of aroma compounds, which are important quality attributes [76].

6.4 Metabolomics

Metabolomics involves the comprehensive analysis of an organism's metabolites, which are the end products of cellular processes [77]. Metabolomic studies provide valuable information on the biochemical pathways involved in plant-pathogen interactions and the biosynthesis of quality-related compounds in fruits [78].

In melon, metabolomic analyses have identified metabolites that are differentially accumulated during the interaction with the fungal pathogen *Fusarium oxysporum* f. sp. *melonis*, providing insights into the metabolic basis of disease resistance [79]. Similarly, metabolomic studies in tomato have revealed the role of specific metabolites, such as volatile organic compounds, in determining fruit flavor and aroma [80].

The integration of omics technologies provides a holistic view of the molecular mechanisms underlying disease resistance and quality traits in horticultural crops [81]. This knowledge can be harnessed to develop novel breeding strategies and biotechnological approaches for crop improvement [82].

7. Challenges and Future Perspectives

Despite the significant advances in biotechnological strategies for enhancing disease resistance and quality parameters in horticultural crops, several challenges remain to be addressed [83]. These challenges include the complexity of plant-pathogen interactions, the environmental influences on quality traits, and the regulatory and public acceptance issues associated with biotechnology-derived products [84].

7.1 Complexity of Plant-Pathogen Interactions

Plant-pathogen interactions are highly complex and dynamic, involving multiple layers of defense responses and counter-defense mechanisms [85]. The development of durable disease resistance in horticultural crops requires a comprehensive understanding of these interactions at the molecular, cellular, and organismal levels [86].

Future research should focus on elucidating the molecular dialogue between plants and pathogens, identifying key pathogenicity factors and their corresponding plant targets, and unraveling the signaling pathways involved in disease resistance [87]. This knowledge will facilitate the design of novel strategies to enhance plant immunity and minimize the impact of pathogens on crop productivity and quality [88].

7.2 Environmental Influences on Quality Traits

The expression of quality traits in horticultural crops is heavily influenced by environmental factors, such as temperature, light, water availability, and nutrient supply [89]. These factors can interact with genetic and physiological processes, leading to significant variations in fruit quality attributes [90].

To develop horticultural crops with consistent and superior quality traits, it is essential to understand the complex interplay between genotype, environment, and management practices [91]. Future research should focus on dissecting the genetic basis of quality traits, identifying environmental cues that regulate their expression, and developing integrated crop management strategies that optimize fruit quality under diverse growing conditions [92].

7.3 Regulatory and Public Acceptance Issues

The commercialization of biotechnology-derived horticultural products faces significant regulatory hurdles and public acceptance issues [93]. The regulatory frameworks governing the development and release of genetically modified (GM) crops vary widely across countries, creating a complex and uncertain landscape for the horticultural industry [94].

Moreover, public perception of GM crops remains a contentious issue, with concerns about potential risks to human health and the environment [95]. Effective communication and engagement with the public are crucial to address these concerns and promote the acceptance of biotechnology-derived horticultural products [96].

Future efforts should focus on harmonizing global regulatory standards, developing science-based risk assessment protocols, and fostering public trust through transparent and inclusive dialogue [97]. Additionally, the development of alternative biotechnological approaches, such as genome editing and cisgenesis, which are perceived as more natural and less controversial, could help mitigate public concerns and facilitate the adoption of biotechnology in the horticultural sector [98].

8. Conclusion

Biotechnological strategies offer immense potential for enhancing disease resistance and quality parameters in horticultural crops. Genetic engineering techniques, such as the introduction of resistance genes, RNAi, and genome editing, provide powerful tools to develop crops with improved resistance to pathogens and superior quality traits. The application of beneficial microorganisms, including PGPRs and mycorrhizal fungi, presents a sustainable approach to promote plant health and productivity. Nanotechnology emerges as a promising avenue for the targeted delivery of antimicrobial agents and plant growth regulators, enabling precise disease control and quality enhancement. Marker-assisted selection accelerates the development of disease-resistant and high-quality varieties by leveraging molecular markers linked to desirable traits.

Omics technologies, encompassing genomics, transcriptomics, proteomics, and metabolomics, offer unprecedented insights into the molecular mechanisms underlying disease resistance and quality attributes. The integration of these technologies provides a holistic view of plant-pathogen interactions and the regulation of fruit development and ripening. However, challenges remain in the complexity of plant-pathogen interactions, the environmental influences on quality traits, and the regulatory and public acceptance issues associated with biotechnology-derived products. Addressing these challenges requires a multidisciplinary approach, involving collaboration among plant scientists, breeders, biotechnologists, policymakers, and stakeholders.

Future research should focus on elucidating the molecular basis of disease resistance and quality traits, developing integrated crop management strategies, harmonizing regulatory standards, and fostering public trust through transparent communication. By harnessing the power of biotechnology and addressing the associated challenges, we can develop sustainable and resilient horticultural crops that meet the growing demands for food security, nutritional quality, and consumer satisfaction.

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Table 1. Examples of genetic engineering approaches for enhancing disease resistance in horticultural crops.

Crop	Gene/Construct	Target Pathogen	Reference
Potato (*Solanum tuberosum*)	*Rpi-blb2*	*Phytophthora infestans*	[11]
Tomato (*Solanum lycopersicum*)	*Bs2*	*Xanthomonas euvesicatoria*	[12]
Papaya (*Carica papaya*)	Coat protein gene (PRSV)	Papaya ringspot virus	[16]
Tomato (*Solanum lycopersicum*)	*Chitin synthase* gene (RNAi)	*Fusarium oxysporum*	[17]
Cucumber (*Cucumis sativus*)	*eIF4E* (CRISPR/Cas9)	Cucumber vein yellowing virus	[21]
Tomato (*Solanum lycopersicum*)	*MLO* (CRISPR/Cas9)	Powdery mildew	[22]

Table 2. Examples of beneficial microorganisms used for disease management in horticultural crops.

Crop	Beneficial Microorganism	Target Pathogen/Disease	Reference
Cucumber (*Cucumis sativus*)	*Bacillus subtilis* QST 713	Powdery mildew	[28]
Tomato (*Solanum lycopersicum*)	*Pseudomonas fluorescens* Pf-5	Bacterial speck	[29]

Tomato (*Solanum lycopersicum*)	*Glomus mosseae* (AMF)	Fusarium wilt	[33]
Strawberry (*Fragaria x ananassa*)	*Laccaria bicolor* (EMF)	*Verticillium dahliae*	[34]
Pepper (*Capsicum annuum*)	*Glomus intraradices* (AMF)	Phytophthora blight	[37]
Potato (*Solanum tuberosum*)	*Glomus intraradices* (AMF)	*Rhizoctonia solani*	[38]

Table 3. Examples of nanotechnology applications for disease control and quality enhancement in horticultural crops.

Crop	Nanoparticle/Nanomaterial	Application	Reference
Tomato (*Solanum lycopersicum*)	Copper oxide nanoparticles	Bacterial spot control	[42]
Wheat (*Triticum aestivum*)	Chitosan nanoparticles loaded with carbendazim	*Fusarium graminearum* control	[43]
Tomato (*Solanum lycopersicum*)	Gibberellic acid-loaded chitosan nanoparticles	Growth and yield improvement	[47]
Banana (*Musa acuminata*)	Ethylene-loaded nanoparticles	Ripening delay and shelf life extension	[48]
Spinach (*Spinacia oleracea*)	Nano-TiO2	Growth enhancement	[48]

Table 4. Examples of marker-assisted selection for disease resistance and quality traits in horticultural crops.

Crop	Trait	Gene/QTL	Reference
Tomato (*Solanum lycopersicum*)	Fusarium wilt resistance	*I-2* gene	[55]
Melon (*Cucumis melo*)	Fusarium wilt resistance	*Fom-2* gene	[56]
Tomato (*Solanum lycopersicum*)	High soluble solids content	*Brix9-2-5* QTL	[59]
Tomato (*Solanum lycopersicum*)	Shelf life	*rin* gene	[59]
Strawberry (*Fragaria x ananassa*)	Fruit firmness	*FaFAD1* gene	[60]
Strawberry (*Fragaria x ananassa*)	Fruit color	*FaMYB10* gene	[60]

Table 5. Examples of omics technologies used to study disease resistance and quality traits in horticultural crops.

Crop	Omics Technology	Application	Reference
Tomato (*Solanum lycopersicum*)	Genomics	Identification of disease resistance genes	[67]
Strawberry (*Fragaria x ananassa*)	Genomics	Identification of fruit quality genes	[68]
Pepper (*Capsicum annuum*)	Transcriptomics	Identification of genes involved in anthracnose resistance	[71]
Citrus (*Citrus* spp.)	Transcriptomics	Identification of genes regulating fruit acidity	[72]
Grapevine (*Vitis vinifera*)	Proteomics	Identification of proteins involved in *Botrytis cinerea* resistance	[75]
Peach (*Prunus persica*)	Proteomics	Identification of proteins associated with fruit softening and aroma	[76]
Melon (*Cucumis melo*)	Metabolomics	Identification of metabolites involved in *Fusarium oxysporum* resistance	[79]
Tomato (*Solanum lycopersicum*)	Metabolomics	Identification of metabolites determining fruit flavor and aroma	[80]

Table 6. Challenges and future perspectives in the application of biotechnology for horticultural crop improvement.

Challenge/Perspective	Description	Reference
Complexity of plant-pathogen interactions	Understanding the molecular basis of disease resistance and the dynamic nature of plant-pathogen interactions	[85], [86]
Environmental influences on quality traits	Elucidating the complex interplay between genotype, environment, and management practices in determining fruit quality	[89], [90]
Regulatory and public acceptance issues	Harmonizing global regulatory standards, developing science-based risk assessment protocols, and fostering public trust in biotechnology-derived products	[93], [94]
Integration of omics technologies	Combining genomics, transcriptomics, proteomics, and metabolomics to gain a holistic understanding of plant responses to biotic and abiotic stresses	[81], [82]
Development of alternative biotechnological approaches	Exploring the potential of genome editing and cisgenesis to mitigate public concerns and facilitate the adoption of biotechnology in horticulture	[97], [98]

10. Figures

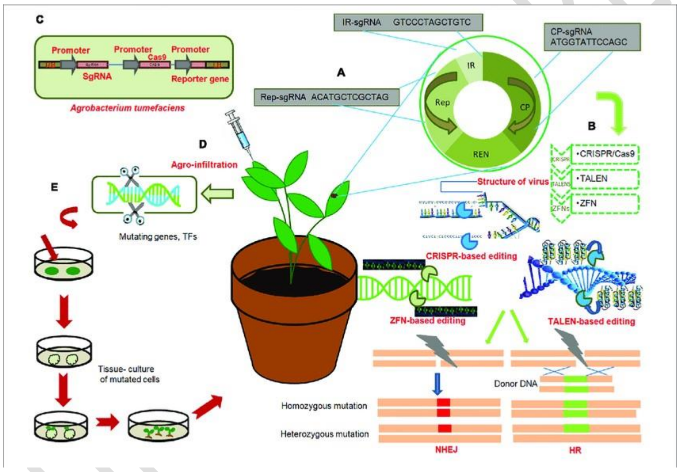

Figure 1. Schematic representation of genetic engineering approaches for enhancing disease resistance in horticultural crops.

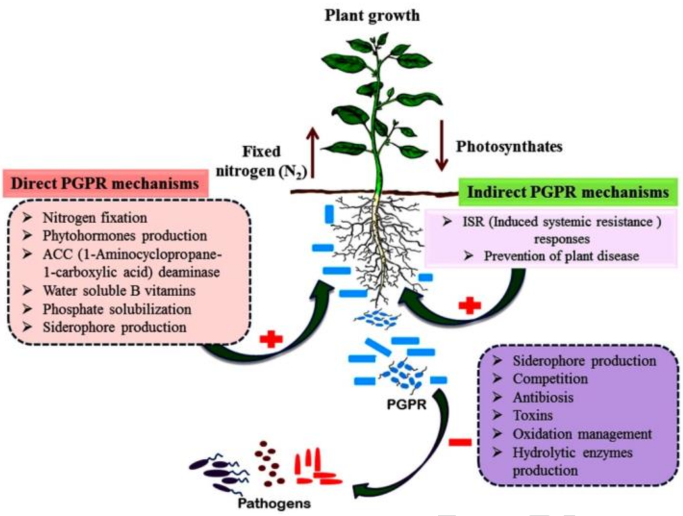

Figure 2. Mechanisms of action of beneficial microorganisms in promoting plant growth and disease resistance. (a) Plant growth-promoting rhizobacteria (PGPR) and (b) mycorrhizal fungi.

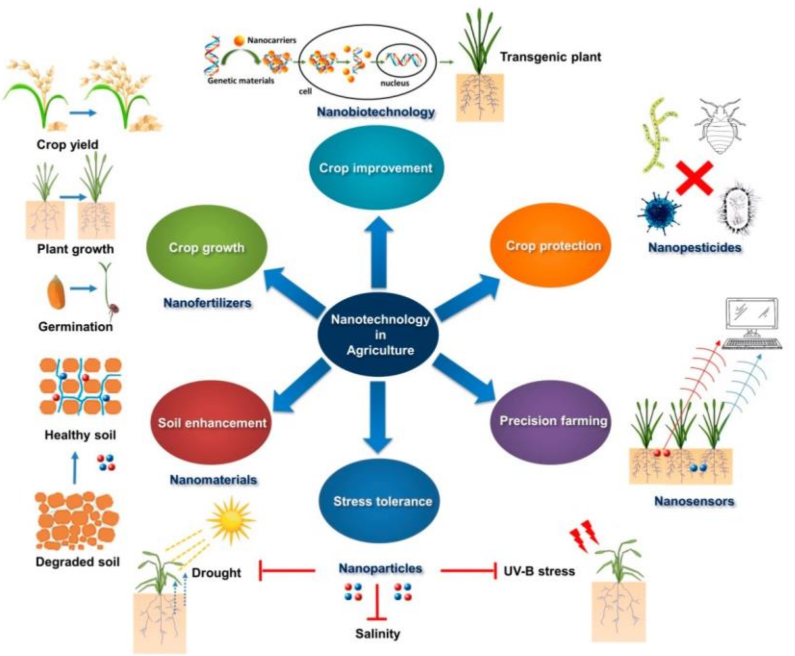

Figure 3. Nanotechnology-based strategies for disease control and quality enhancement in horticultural crops.

Table 7. Examples of horticultural crops and their major diseases

Crop	Major Diseases	Causal Agents	Reference
Tomato (*Solanum lycopersicum*)	Bacterial spot, Bacterial speck, Bacterial canker, Early blight, Late blight, Fusarium wilt, Verticillium wilt, Tomato yellow leaf curl virus	*Xanthomonas spp.*, *Pseudomonas syringae* pv. *tomato*, *Clavibacter michiganensis* subsp. *michiganensis*, *Alternaria solani*, *Phytophthora infestans*, *Fusarium oxysporum* f. sp. *lycopersici*, *Verticillium dahliae*, Tomato yellow leaf curl virus	[99]
Potato (*Solanum tuberosum*)	Late blight, Early blight, Bacterial soft rot, Potato virus Y, Potato leafroll virus	*Phytophthora infestans*, *Alternaria solani*, *Pectobacterium carotovorum*, Potato virus Y, Potato leafroll virus	[100]
Pepper (*Capsicum* spp.)	Bacterial spot, Phytophthora blight, Cucumber mosaic virus, Pepper mild mottle virus	*Xanthomonas spp.*, *Phytophthora capsici*, Cucumber mosaic virus, Pepper mild mottle virus	[101]
Cucumber (*Cucumis sativus*)	Downy mildew, Powdery mildew, Angular leaf spot, Cucumber mosaic virus	*Pseudoperonospora cubensis*, *Sphaerotheca fuliginea*, *Pseudomonas syringae* pv. *lachrymans*, Cucumber mosaic virus	[102]
Grapevine (*Vitis vinifera*)	Downy mildew, Powdery mildew, Botrytis bunch rot, Grapevine fanleaf virus	*Plasmopara viticola*, *Erysiphe necator*, *Botrytis cinerea*, Grapevine fanleaf virus	[103]
Citrus (*Citrus* spp.)	Huanglongbing (Citrus greening), Citrus canker, Citrus tristeza virus, Citrus black spot	*Candidatus* Liberibacter asiaticus, *Xanthomonas citri* subsp. *citri*, Citrus tristeza virus, *Phyllosticta citricarpa*	[104]
Apple (*Malus domestica*)	Apple scab, Fire blight, Powdery mildew, Apple mosaic virus	*Venturia inaequalis*, *Erwinia amylovora*, *Podosphaera leucotricha*, Apple mosaic virus	[105]
Strawberry (*Fragaria x ananassa*)	Gray mold, Powdery mildew, Anthracnose, Strawberry crinkle virus	*Botrytis cinerea*, *Sphaerotheca macularis*, *Colletotrichum acutatum*, Strawberry crinkle virus	[106]
Peach (*Prunus persica*)	Brown rot, Peach leaf curl, Peach scab, Plum pox virus	*Monilinia fructicola*, *Taphrina deformans*, *Cladosporium carpophilum*, Plum pox virus	[107]
Mango (*Mangifera indica*)	Anthracnose, Powdery mildew, Bacterial black spot, Mango malformation	*Colletotrichum gloeosporioides*, *Oidium mangiferae*, *Xanthomonas citri* pv. *mangiferaeindicae*, *Fusarium* spp.	[108]

Table 8. Biotechnology companies involved in developing disease-resistant and quality-enhanced horticultural crops

Company	Crop	Trait/Technology	Reference
Monsanto (Bayer)	Tomato, Pepper, Cucumber	Disease resistance (Bt, Virus-resistant)	[109]
Syngenta	Tomato, Pepper, Melon	Disease resistance (Fusarium, Bacterial spot, Virus-resistant)	[110]
Bayer CropScience	Tomato, Cucumber, Lettuce	Disease resistance (Fusarium, Downy mildew, Virus-resistant)	[111]
Dow AgroSciences (Corteva)	Potato, Tomato, Lettuce	Disease resistance (Late blight, Bacterial spot, Downy mildew)	[112]

DuPont (Corteva)	Tomato, Melon, Squash	Disease resistance (Bacterial spot, Powdery mildew, Virus-resistant)	[113]
Keygene	Pepper, Cucumber, Lettuce	Disease resistance (Bacterial spot, Downy mildew, Fusarium)	[114]
Rijk Zwaan	Tomato, Pepper, Cucumber	Disease resistance (Fusarium, Bacterial spot, Powdery mildew)	[115]
Enza Zaden	Tomato, Pepper, Melon	Disease resistance (Fusarium, Bacterial spot, Powdery mildew)	[116]
Sakata Seed	Tomato, Pepper, Broccoli	Disease resistance (Bacterial spot, Downy mildew, Clubroot)	[117]
Takii Seed	Tomato, Pepper, Spinach	Disease resistance (Fusarium, Bacterial spot, Downy mildew)	[118]

Table 9. Regulatory agencies and their roles in the approval of biotechnology-derived horticultural crops

Agency	Country/Region	Role	Reference
United States Department of Agriculture (USDA)	United States	Regulates the importation, interstate movement, and environmental release of genetically engineered organisms	[119]
Environmental Protection Agency (EPA)	United States	Regulates the use of plant-incorporated protectants (PIPs) and determines the safety of pesticides	[120]
Food and Drug Administration (FDA)	United States	Ensures the safety and proper labeling of food and feed products derived from genetically engineered crops	[121]
European Food Safety Authority (EFSA)	European Union	Conducts risk assessments and provides scientific advice on genetically modified organisms (GMOs)	[122]
Health Canada	Canada	Assesses the safety of novel foods, including those derived from biotechnology	[123]
Canadian Food Inspection Agency (CFIA)	Canada	Regulates the environmental release, variety registration, and import/export of plants with novel traits (PNTs)	[124]
Ministry of Agriculture, Forestry and Fisheries (MAFF)	Japan	Regulates the development, cultivation, and distribution of genetically modified crops	[125]
Ministry of Health, Labour and Welfare (MHLW)	Japan	Assesses the safety of food and feed products derived from genetically modified crops	[126]
Office of the Gene Technology Regulator (OGTR)	Australia	Regulates the development and release of genetically modified organisms (GMOs)	[127]
Food Standards Australia New Zealand (FSANZ)	Australia & New Zealand	Assesses the safety of genetically modified foods and ensures proper labeling	[128]

Table 10. Public perception and acceptance of biotechnology-derived horticultural crops

Country/Region	Acceptance Level	Influencing Factors	Reference

United States	Moderate to High	Trust in regulatory agencies, perceived benefits, familiarity with technology	[129]
European Union	Low to Moderate	Concerns about safety, environmental impact, ethical considerations, lack of perceived benefits	[130]
Canada	Moderate	Trust in regulatory agencies, perceived benefits, concerns about long-term effects	[131]
Japan	Low to Moderate	Concerns about safety, environmental impact, cultural values, lack of perceived benefits	[132]
Australia	Moderate	Trust in regulatory agencies, perceived benefits, concerns about safety and environmental impact	[133]
New Zealand	Low to Moderate	Concerns about safety, environmental impact, cultural values, lack of perceived benefits	[134]
China	Moderate to High	Perceived benefits, trust in government, limited public debate	[135]
India	Low to Moderate	Concerns about safety, environmental impact, socio-economic implications, lack of public awareness	[136]
Brazil	Moderate to High	Perceived benefits, trust in regulatory agencies, limited public debate	[137]
Mexico	Low to Moderate	Concerns about safety, environmental impact, cultural values, socio-economic implications	[138]

Table 11. Socio-economic impacts of adopting biotechnology-derived horticultural crops

Impact Category	Potential Benefits	Potential Challenges	Reference
Crop Productivity	Increased yield, reduced crop losses due to pests and diseases, improved stress tolerance	Increased seed costs, potential for reduced genetic diversity, dependence on technology providers	[139]
Farmer Livelihoods	Increased income, reduced input costs (e.g., pesticides), improved crop quality and marketability	Increased seed costs, potential for market concentration, intellectual property issues	[140]
Food Security	Increased food availability, improved nutritional quality, reduced food prices	Unequal access to technology, potential for reduced crop diversity, concerns about long-term effects	[141]
Environmental Sustainability	Reduced pesticide use, improved resource-use efficiency (e.g., water, nutrients), reduced environmental footprint	Potential for gene flow to wild relatives, impacts on non-target organisms, development of resistant pests	[142]
Consumer Choice	Improved product quality, increased variety of available products, potential health benefits	Concerns about safety and long-term effects, labeling and traceability issues, ethical considerations	[143]
International Trade	Increased trade opportunities, harmonization of regulatory frameworks, technology transfer	Trade barriers due to differing regulations, potential for market concentration, intellectual property disputes	[144]
Research and Innovation	Increased investment in agricultural research, development of new tools and technologies, knowledge spillovers	Concentration of research in private sector, intellectual property barriers, public funding constraints	[145]

Capacity Building	Strengthening of local research and development capabilities, technology transfer, training and education	Unequal access to technology and knowledge, brain drain, dependence on external expertise	[146]
Public Engagement	Increased public awareness and participation in decision-making, improved science communication, trust-building	Polarization of public opinion, misinformation and misconceptions, lack of effective engagement mechanisms	[147]
Policy and Regulation	Development of science-based regulatory frameworks, international harmonization, stakeholder participation	Regulatory gaps and inconsistencies, lack of public trust, politicization of decision-making	[148]

Table 12. Strategies for improving public acceptance of biotechnology-derived horticultural crops

Strategy	Description	Examples	Reference
Transparency and Openness	Providing clear, accessible, and balanced information about biotechnology-derived crops, their development process, and the regulatory oversight	Public information campaigns, open data initiatives, stakeholder engagement	[149]
Science Communication	Communicating the scientific basis, benefits, and potential risks of biotechnology-derived crops in an understandable and engaging manner	Science outreach programs, media training for researchers, science-based content creation	[150]
Stakeholder Engagement	Involving diverse stakeholders (e.g., farmers, consumers, NGOs) in the development, assessment, and decision-making processes related to biotechnology-derived crops	Participatory breeding programs, citizen science initiatives, multi-stakeholder dialogues	[151]
Addressing Ethical Concerns	Recognizing and addressing ethical concerns related to biotechnology-derived crops, such as equity, justice, and respect for cultural values	Ethical impact assessments, value-sensitive design, inclusive innovation	[152]
Benefit Sharing	Ensuring that the benefits of biotechnology-derived crops are fairly distributed among different stakeholders, particularly smallholder farmers and local communities	Benefit-sharing agreements, technology transfer programs, capacity building	[153]
Labeling and Traceability	Implementing clear and consistent labeling and traceability systems for biotechnology-derived crops and their products, enabling informed consumer choice	Mandatory or voluntary labeling schemes, supply chain transparency, digital traceability solutions	[154]
Responsible Innovation	Integrating social, ethical, and environmental considerations into the research, development, and commercialization of biotechnology-derived crops	Responsible research and innovation (RRI) frameworks, life cycle assessments, socio-economic impact assessments	[155]
Public-Private Partnerships	Fostering collaborations between public research institutions, private companies, and other stakeholders to develop and deploy biotechnology-	Joint research projects, technology transfer agreements, cross-sector innovation networks	[156]

	derived crops that address societal needs		
Capacity Building and Education	Strengthening the capacity of researchers, policymakers, and other stakeholders to develop, assess, and regulate biotechnology-derived crops, and promoting public education and awareness	Training programs, curriculum development, international collaborations, public outreach initiatives	[157]
Adaptive Governance	Developing flexible and responsive governance frameworks that can adapt to the rapidly evolving landscape of biotechnology-derived crops, while ensuring public trust and engagement	Anticipatory governance, regulatory sandboxes, participatory technology assessment	[158]