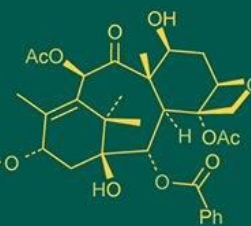
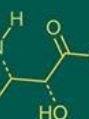
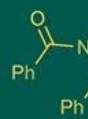


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Role of elicitors in the plant defense mechanism: A comprehensive review

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Abstract

Plants are constantly exposed to a wide range of biotic and abiotic stresses, including pathogens, pests and environmental challenges. To survive, they have evolved sophisticated defense mechanisms that can be activated upon recognition of specific signals known as elicitors. Elicitors are molecules that trigger physiological and biochemical responses in plants, leading to enhanced resistance. These compounds may originate from pathogens, host plants, or external sources and can induce a cascade of defense responses such as the production of reactive oxygen species (ROS), phytoalexins, pathogenesis-related proteins, and strengthening of cell walls. This review provides a comprehensive overview of different types of elicitors, their modes of action, signalling pathways and their role in inducing systemic resistance in plants. Additionally, the application of elicitors in sustainable agriculture and crop protection strategies is discussed. Understanding elicitor-mediated plant defense responses offers promising opportunities for developing eco-friendly alternatives to chemical pesticides and enhancing crop resilience.

Keywords: Elicitors, plant defense responses, biotic and abiotic stress, signal transduction, reactive oxygen species (ROS), systemic resistance, pathogenesis-related proteins, sustainable agriculture

1. Introduction

Plants, as sessile organisms, are constantly exposed to a wide range of environmental challenges that threaten their growth, development, and survival. These challenges include biotic stresses such as pathogens (bacteria, fungi, viruses, and nematodes) and herbivorous insects, as well as abiotic stresses such as drought, salinity, extreme temperatures, and ultraviolet radiation. Unlike animals, plants do not possess a circulatory immune system or mobile defense cells ^[1]. Instead, they rely on an intricate and highly coordinated innate immune system that enables them to detect and respond to external stimuli effectively. One of the key components of this defense system is the recognition of elicitors—molecules that trigger plant defense responses ^[2]. Elicitors are defined as substances that stimulate a physiological or biochemical response in plants, particularly those associated with defense mechanisms. These molecules can originate from a variety of sources, including invading pathogens, beneficial microorganisms, damaged plant tissues, or environmental factors. Based on their origin, elicitors are broadly classified into biotic and abiotic types, while those produced within the plant are referred to as endogenous elicitors ^[3]. Regardless of their source, elicitors play a crucial role in activating plant immunity by initiating signalling pathways that lead to the expression of defense-related genes. The concept of elicitation has been central to plant pathology and plant physiology research for several decades. Early studies demonstrated that plants could recognize specific components of pathogens and respond by producing antimicrobial compounds ^[4]. This led to the identification of pathogen-associated molecular patterns (PAMPs), which are conserved molecules such as chitin from fungal cell walls or flagellin from bacterial flagella. These molecules are recognized by plant cells through specialized receptors known as pattern recognition receptors (PRRs), located on the plasma membrane. The interaction between PAMPs and PRRs triggers a defense response known as PAMP-triggered immunity (PTI), which forms the first line of defense against invading pathogens ^[5]. In addition to PAMPs, plants also recognize damage-associated molecular patterns (DAMPs), which are endogenous molecules released during tissue damage.

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These molecules serve as internal warning signals that activate defense responses even in the absence of pathogens. Furthermore, certain pathogens produce effector molecules that can suppress plant immunity; however, plants have evolved resistance (R) proteins that recognize these effectors and activate a stronger defense response known as effector-triggered immunity (ETI). Together, PTI and ETI constitute a robust immune system that enables plants to combat a wide range of biotic stresses.

The recognition of elicitors initiates a cascade of molecular events within the plant cell. These events include rapid changes in ion fluxes, particularly calcium influx, production of reactive oxygen species (ROS), activation of mitogen-activated protein kinase (MAPK) pathways, and modulation of phytohormone signalling networks [6]. These signalling pathways work in a coordinated manner to regulate the expression of defense-related genes and the synthesis of protective compounds. For instance, salicylic acid is primarily associated with defense against biotrophic pathogens, while jasmonic acid and ethylene play key roles in defense against necrotrophic pathogens and herbivorous insects. One of the most remarkable features of elicitor-induced plant defense is its ability to confer systemic resistance. Upon local recognition of an elicitor, plants can activate defense responses in distant tissues, providing long-lasting protection against subsequent attacks. This phenomenon is known as systemic acquired resistance (SAR) or induced systemic resistance (ISR), depending on the signalling pathways involved. These systemic responses are particularly important for enhancing overall plant immunity and improving resilience under field conditions [7]. In recent years, there has been growing interest in the practical applications of elicitors in agriculture. The excessive use of chemical pesticides has led to environmental pollution, development of resistant pathogen strains, and adverse effects on human health. As a result, there is an urgent need for sustainable and eco-friendly alternatives. Elicitors offer a promising solution by enhancing the plant's natural defense mechanisms without causing harm to the environment. Various elicitors, such as chitosan, salicylic acid, and plant-derived extracts, have been successfully used to improve crop resistance against diseases and pests.

Advances in molecular biology, genomics and biotechnology have significantly expanded our understanding of elicitor-mediated plant defense mechanisms. High-throughput techniques such as transcriptomics, proteomics, and metabolomics have enabled researchers to identify key genes, proteins, and metabolic pathways involved in defense responses. These technologies have also facilitated the discovery of novel elicitors and their mechanisms of action. Moreover, genetic engineering approaches are being explored to enhance plant responsiveness to elicitors, thereby improving resistance and productivity [8]. Despite these advancements, several challenges remain in the effective utilization of elicitors in agriculture. Plant responses to elicitors can vary depending on species, developmental stage, and environmental conditions. Additionally, the complexity of signalling networks and cross-talk between different pathways makes it difficult to predict outcomes under field conditions. Therefore, further research is needed to optimize elicitor application strategies and to understand their interactions

with other agronomic practices [9]. Another emerging area of interest is the integration of elicitor-based approaches with modern technologies such as nanotechnology and precision agriculture. Nanoparticles can be used as carriers for elicitors, improving their stability, delivery, and effectiveness. Similarly, precision agriculture tools can help in the targeted application of elicitors, ensuring optimal usage and minimizing wastage. These innovations have the potential to revolutionize crop protection and contribute to sustainable agricultural systems, elicitors play a fundamental role in the plant defense mechanism by acting as key signalling molecules that activate a wide range of protective responses. Their ability to enhance plant immunity, coupled with their eco-friendly nature, makes them valuable tools for sustainable agriculture. Understanding the molecular basis of elicitor action and their interactions with plant signalling networks will be crucial for developing effective strategies to improve crop resilience and productivity. This review aims to provide a comprehensive overview of the role of elicitors in plant defense mechanisms, highlighting their significance in modern agriculture and future prospects.

2. Types of Elicitors

2. Classification and Types of Elicitors

Elicitors are a diverse group of molecules that play a crucial role in activating plant defense responses. Their classification is primarily based on origin, chemical nature, and mode of action. Understanding the different types of elicitors is essential for elucidating their functional roles in plant immunity and for exploiting their potential applications in agriculture and biotechnology [10]. Broadly, elicitors can be categorized into biotic, abiotic, and endogenous elicitors, although further subdivisions exist based on their structural and functional characteristics.

2.1 Biotic Elicitors

Biotic elicitors are derived from living organisms, including pathogens, insects, and beneficial microbes. These elicitors are often recognized as non-self-molecules by the plant immune system and trigger defense responses aimed at restricting pathogen invasion or herbivore damage.

2.1.1 Pathogen-Associated Molecular Patterns (PAMPs)

PAMPs are highly conserved molecular signatures found in groups of pathogens. These molecules are essential for pathogen survival and are therefore less likely to undergo mutation, making them reliable indicators of microbial presence. Common examples include chitin from fungal cell walls, flagellin from bacterial flagella, β -glucans, and lipopolysaccharides (LPS) from bacterial outer membranes [11]. Recognition of PAMPs by plant pattern recognition receptors (PRRs) initiates PAMP-triggered immunity (PTI), which serves as the first line of defense.

2.1.2 Microbe-Associated Molecular Patterns (MAMPs)

Closely related to PAMPs, MAMPs are derived not only from pathogenic organisms but also from non-pathogenic and beneficial microbes. For example, certain rhizobacteria produce molecules that can induce plant defense responses without causing disease. These beneficial interactions often lead to induced systemic resistance (ISR), which enhances the plant's ability to resist future pathogen attacks.

2.1.3 Herbivore-Associated Molecular Patterns (HAMPs)

Plants can also detect molecules associated with herbivorous insects. These elicitors are typically present in insect saliva, oral secretions, or oviposition fluids. Compounds such as fatty acid–amino acid conjugates (FACs), inceptins, and volicitin act as signals that activate defense responses against herbivory [12]. These responses include the production of protease inhibitors, toxic secondary metabolites, and volatile organic compounds that attract natural predators of the herbivores.

2.1.4 Fungal and Bacterial Elicitors

Specific molecules secreted by pathogens can act as elicitors. For example, fungal elicitors such as ergosterol and elicitor proteins can trigger defense responses. Similarly, bacterial proteins and polysaccharides can activate plant immunity. These elicitors often function as virulence factors but are recognized by plants as signals of infection.

2.2 Abiotic Elicitors

Abiotic elicitors are non-biological factors that can induce

defense responses in plants. These elicitors are often associated with environmental stress conditions and can mimic the effects of biotic elicitors by activating similar signalling pathways.

2.2.1 Physical Elicitors

Physical factors such as ultraviolet (UV) radiation, temperature extremes (heat and cold), and mechanical injury can act as elicitors. For instance, UV-B radiation can stimulate the production of flavonoids and other protective compounds that help mitigate damage caused by radiation stress.

2.2.2 Chemical Elicitors

Chemical elicitors include a wide range of compounds that can artificially or naturally induce plant defense responses. Important examples include salicylic acid, jasmonic acid, ethylene, hydrogen peroxide, and nitric oxide. These molecules are often involved in plant signalling pathways and can be applied exogenously to enhance resistance. Synthetic chemicals such as benzothiadiazole (BTH) are also widely used as elicitors in agriculture.

Table 1: Classification of Elicitors Based on Origin

Type of Elicitor	Source	Examples	Primary Function
Biotic Elicitors	Pathogens, microbes, insects	Chitin, flagellin, lipopolysaccharides	Trigger immune response (PTI/ETI)
Abiotic Elicitors	Environmental factors	UV radiation, temperature, heavy metals	Induce stress-related defense pathways
Endogenous Elicitors	Plant-derived	Oligogalacturonides, systemin	Signal internal damage and activate defense

Table 2: Classification Based on Chemical Nature

Chemical Type	Examples	Role in Defense
Carbohydrates	Chitin, β -glucans	Recognized by PRRs, induce immunity
Proteins/Peptides	Flagellin, systemin	Activate signalling pathways
Lipids	Jasmonic acid derivatives	Regulate defense signalling
Phenolics	Salicylic acid	Induce systemic resistance

Table 3: Key Receptors and Their Corresponding Elicitors

Receptor (PRR)	Recognized Elicitor	Source	Response Triggered
FLS2	Flagellin	Bacteria	PAMP-triggered immunity
CERK1	Chitin	Fungi	Defense gene activation
EFR	EF-Tu protein	Bacteria	Immune signalling
PEPR	Peptide elicitors	Plant (DAMPs)	Systemic defense activation

Table 4: Signal Transduction Components in Elicitor Response

Component	Function	Outcome
ROS (Reactive Oxygen Species)	Antimicrobial and signalling	Oxidative burst
Ca^{2+} ions	Secondary messenger	Activation of kinases
MAPK cascade	Signal amplification	Gene expression regulation
Phytohormones (SA, JA, ET)	Defense signalling	Systemic resistance

Table 5: Defense Responses Induced by Elicitors

Defense Mechanism	Description	Biological Significance
Phytoalexin production	Antimicrobial compounds	Inhibits pathogen growth
PR protein synthesis	Chitinases, glucanases	Degrades pathogen cell walls
Cell wall reinforcement	Lignin, callose deposition	Prevents pathogen entry
Hypersensitive response	Localized cell death	Restricts pathogen spread

Table 6: Systemic Resistance Types

Type	Signalling Molecule	Inducing Agent	Characteristics
SAR (Systemic Acquired Resistance)	Salicylic acid	Pathogen infection	Long-lasting, broad-spectrum
ISR (Induced Systemic Resistance)	Jasmonic acid, ethylene	Beneficial microbes	Priming effect, energy efficient

Table 7: Elicitors Used in Agriculture

Elicitor	Source	Application	Effect
Chitosan	Fungal cell wall	Foliar spray	Enhances disease resistance
Salicylic acid	Plant hormone	Seed/foliar treatment	Induces SAR
Jasmonic acid	Plant hormone	Stress treatment	Improves insect resistance
Benzothiadiazole (BTH)	Synthetic	Crop protection	Mimics SAR

Table 8: Role of Elicitors in Secondary Metabolite Production

Elicitor	Target Metabolite	Plant System	Effect
Methyl jasmonate	Alkaloids	Catharanthus roseus	Increased yield
Chitosan	Phenolics	Various plants	Enhanced antioxidant activity
Salicylic acid	Flavonoids	Medicinal plants	Improved bioactivity

3. Perception and Recognition of Elicitors

The perception and recognition of elicitors represent the initial and most critical step in the activation of plant defense mechanisms. Plants possess a sophisticated surveillance system that allows them to detect external and internal signals indicative of stress or pathogen attack. This detection is primarily mediated by specialized receptors known as pattern recognition receptors (PRRs), which are localized on the plasma membrane of plant cells. These receptors play a key role in identifying conserved molecular patterns associated with pathogens or damage, thereby initiating immune responses [13]. When elicitor molecules such as pathogen-associated molecular patterns (PAMPs) or damage-associated molecular patterns (DAMPs) come into contact with plant cells, they bind to specific PRRs. This ligand–receptor interaction leads to the activation of receptor-like kinases (RLKs) or receptor-like proteins (RLPs), which function as signaling hubs. One well-studied example is the FLS2 receptor, which recognizes bacterial flagellin, and the CERK1 receptor, which detects chitin fragments from fungal cell walls. Upon binding of the elicitor, these receptors undergo conformational changes and form complexes with co-receptors such as BAK1, leading to the activation of intracellular signaling cascades. The recognition process is highly specific and allows plants to distinguish between self and non-self-molecules. This specificity ensures that defense responses are activated only when necessary, preventing unnecessary energy expenditure. In addition to PRRs, plants also possess intracellular receptors known as nucleotide-binding leucine-rich repeat (NLR) proteins. These receptors detect pathogen-derived effector molecules that bypass the initial immune response. The activation of NLR proteins leads to a stronger and more rapid defense response known as effector-triggered immunity (ETI) [14]. Following elicitor recognition, a series of early cellular events occur within seconds to minutes. These include changes in membrane potential, ion fluxes such as calcium influx and proton efflux, and activation of protein phosphorylation pathways. These early responses serve as signals that amplify the defense response and prepare the plant for subsequent reactions. Calcium ions, in particular, act as important secondary messengers that regulate various downstream processes [15]. Another key aspect of elicitor recognition is the formation of receptor complexes and signal amplification. The binding of elicitors to PRRs often leads to receptor clustering and the recruitment of additional signaling proteins. This process enhances the sensitivity and efficiency of the immune response. Moreover, cross-talk between different receptor systems allows plants to integrate multiple signals and mount a coordinated defense response.

The perception of elicitors is not limited to pathogen detection but also includes the recognition of beneficial microbes. In such cases, plants modulate their responses to allow symbiotic interactions while still maintaining defense readiness. This ability to differentiate between harmful and beneficial organisms highlights the complexity of plant immune systems [16], the perception and recognition of elicitors involve a highly regulated network of receptors and signalling molecules that enable plants to detect and respond to a wide range of stimuli. This process forms the foundation of plant immunity and determines the effectiveness of subsequent defense responses.

4. Signal Transduction Mechanisms

Following the recognition of elicitors, plants activate a complex network of signal transduction pathways that translate external signals into appropriate defense responses. These signalling mechanisms involve a series of biochemical and molecular events that amplify the initial signal and regulate gene expression. The efficiency of these pathways determines the strength and effectiveness of the plant's defense response [17-18]. One of the earliest events in signal transduction is the rapid production of reactive oxygen species (ROS), commonly referred to as the oxidative burst. Molecules such as hydrogen peroxide and superoxide radicals are generated at the site of elicitor recognition. These ROS serve dual functions: they act as antimicrobial agents that directly inhibit pathogen growth and as signalling molecules that activate downstream defense pathways. The controlled production and scavenging of ROS are essential to prevent cellular damage while maintaining effective signalling.

Calcium signalling is another critical component of elicitor-induced signal transduction. Upon elicitor perception, there is a rapid influx of calcium ions into the cytoplasm from extracellular spaces or intracellular stores. These calcium signals are decoded by calcium-binding proteins such as calmodulin and calcium-dependent protein kinases (CDPKs). These proteins then activate various downstream targets, including transcription factors and metabolic enzymes, leading to the expression of defense-related genes [19-20]. Mitogen-activated protein kinase (MAPK) cascades play a central role in amplifying and transmitting signals within the cell. These cascades consist of a series of phosphorylation events involving MAP kinase kinase kinases (MAPKKKs), MAP kinase kinases (MAPKKs), and MAP kinases (MAPKs). Activation of MAPKs leads to the regulation of transcription factors that control the expression of genes involved in defense, stress response, and metabolism. The MAPK pathway is highly conserved and is one of the most important signalling modules in plant

immunity^[22]. Phytohormone signalling pathways are also integral to elicitor-mediated responses. Salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) are the hormones involved in plant defense. SA is primarily associated with resistance against biotrophic pathogens and is a key regulator of systemic acquired resistance. JA and ET, on the other hand, are involved in defense against necrotrophic pathogens and herbivorous insects. These hormones interact through complex cross-talk mechanisms, allowing plants to fine-tune their responses based on the type of stress encountered^[23-24]. In addition to these major pathways, other signalling molecules such as nitric oxide (NO) and cyclic nucleotides also contribute to signal transduction. Nitric oxide interacts with ROS to regulate defense responses and cell death processes. Furthermore, secondary messengers such as phospholipids and inositol phosphates play roles in membrane signalling and intracellular communication.

Signal transduction ultimately leads to the activation of transcription factors such as WRKY, MYB, and NAC families, which regulate the expression of defense-related genes. These genes encode proteins involved in antimicrobial activity, cell wall reinforcement, and stress tolerance. The coordinated regulation of these genes ensures an effective and timely defense response. Overall, signal transduction mechanisms in plants represent a highly dynamic and interconnected network that integrates multiple signals and regulates defense responses at the molecular level^[25]. Understanding these pathways is essential for developing strategies to enhance plant resistance and improve agricultural productivity.

5. Defense Responses Induced by Elicitors

Upon successful perception and signal transduction, elicitors activate a wide range of defense responses that collectively enhance the plant's ability to resist pathogen invasion and environmental stress. These responses are both rapid and long-term, involving biochemical, structural, and molecular changes within the plant system. The primary aim of these responses is to limit pathogen growth, prevent spread, and strengthen plant tissues. One of the earliest and most significant responses is the production of phytoalexins, which are low-molecular-weight antimicrobial compounds synthesized *de novo* in response to stress^[26]. These compounds, including flavonoids, terpenoids, and alkaloids, possess strong antimicrobial properties and inhibit the growth of invading pathogens. Their accumulation at the site of infection forms a chemical barrier that restricts pathogen proliferation. Another critical defense mechanism involves the synthesis of pathogenesis-related (PR) proteins^[27]. These proteins include enzymes such as chitinases and β -1,3-glucanases, which degrade the structural components of fungal cell walls. Other PR proteins function as proteinase inhibitors, lectins, or antimicrobial peptides, contributing to enhanced resistance. The expression of PR proteins is often used as a molecular marker for plant defense activation.

Elicitors also induce cell wall reinforcement, which serves as a physical barrier against pathogen entry. This process involves the deposition of structural polymers such as lignin, callose, and suberin in the cell wall. These compounds increase the rigidity and impermeability of the cell wall, making it more difficult for pathogens to penetrate. Additionally, cross-linking of cell wall proteins

further strengthens the structural integrity of plant tissues^[28]. The hypersensitive response (HR) is another important defense strategy triggered by elicitors. HR is characterized by localized programmed cell death at the site of infection, which limits the spread of biotrophic pathogens that depend on living host cells. This response is often accompanied by the accumulation of ROS and antimicrobial compounds, creating a hostile environment for pathogens. In addition to localized responses, elicitors can induce the production of defensive enzymes such as peroxidases, polyphenol oxidases, and phenylalanine ammonia-lyase (PAL). These enzymes play key roles in the synthesis of phenolic compounds and lignin, as well as in detoxification processes. Their activity contributes to both structural and chemical defense mechanisms^[29]. Furthermore, elicitor-induced responses include the production of volatile organic compounds (VOCs) that serve as signalling molecules. These VOCs can attract natural predators of herbivores or signal neighbouring plants to activate their defense systems. This form of communication highlights the complex ecological interactions involved in plant defense. Overall, elicitor-induced defense responses are multifaceted and highly coordinated. They involve a combination of chemical, structural, and molecular strategies that work together to enhance plant resistance. The effectiveness of these responses depends on the type of elicitor, plant species, and environmental conditions.

6. Systemic Resistance Mechanisms

In addition to localized defense responses, elicitors play a crucial role in activating systemic resistance mechanisms that provide long-term protection throughout the plant. These systemic responses enable plants to "prepare" distant tissues for potential future attacks, thereby enhancing overall immunity^[30]. The two forms of systemic resistance are Systemic Acquired Resistance (SAR) and Induced Systemic Resistance (ISR).

Systemic Acquired Resistance (SAR) is typically triggered by localized infection or exposure to certain elicitors. It is primarily mediated by the signalling molecule salicylic acid (SA). Once activated, SAR leads to the accumulation of SA in both local and distant tissues, resulting in the expression of pathogenesis-related (PR) genes. This response provides broad-spectrum resistance against a wide range of pathogens, particularly biotrophic organisms. SAR is characterized by its long-lasting effect and ability to enhance resistance even in uninfected parts of the plant^[31]. Induced Systemic Resistance (ISR), on the other hand, is generally associated with beneficial microbes such as plant growth-promoting rhizobacteria (PGPR). Unlike SAR, ISR is mediated by jasmonic acid (JA) and ethylene (ET) signalling pathways. ISR does not typically involve the accumulation of PR proteins but enhances the plant's defensive capacity by priming it for faster and stronger responses upon pathogen attack. This "primed state" allows plants to respond more efficiently to stress without incurring significant metabolic costs. A key feature of systemic resistance is signal translocation, where signalling molecules produced at the site of elicitor recognition are transported to distant tissues. These signals may include phytohormones, peptides, and mobile metabolites. Recent studies have also suggested the involvement of small RNAs and electrical signals in long-distance communication within plants.

Another important aspect is the cross-talk between SAR and ISR pathways. Although these pathways are regulated by different hormones, they are not mutually exclusive. Instead, they interact in a complex manner to fine-tune the defense response based on the type of stress encountered. This cross-talk ensures that plants can mount an appropriate and efficient defense strategy. Systemic resistance also contributes to memory-like responses in plants, where prior exposure to elicitors enhances the response to subsequent attacks. This phenomenon, often referred to as “priming,” is gaining attention as a potential strategy for improving crop resilience, systemic resistance mechanisms extend the protective effects of elicitors beyond the initial site of perception, providing comprehensive and long-lasting defense. These mechanisms are essential for plant survival in natural environments and have significant implications for agricultural practices.

7. Role of Elicitors in Secondary Metabolite Production

Elicitors play a vital role in enhancing the production of secondary metabolites in plants, which are compounds not directly involved in growth and development but are crucial for defense and adaptation. These metabolites include alkaloids, flavonoids, phenolics, terpenoids, and other bioactive compounds that possess antimicrobial, antioxidant, and medicinal properties. The application of elicitors stimulates specific biosynthetic pathways that lead to increased accumulation of these compounds. For example, elicitors such as methyl jasmonate, salicylic acid, and chitosan are known to activate genes involved in the phenylpropanoid pathway, resulting in enhanced production of phenolic compounds and flavonoids. These compounds not only protect plants against pathogens but also contribute to their nutritional and pharmaceutical value. One of the key mechanisms underlying elicitor-induced secondary metabolite production is the activation of transcription factors that regulate biosynthetic genes. Transcription factors such as MYB, WRKY, and bHLH families play a central role in controlling the expression of enzymes involved in metabolite synthesis. The coordinated regulation of these genes ensures efficient production of defense-related compounds. Elicitors are widely used in plant tissue culture and in vitro systems to enhance the production of valuable metabolites. In these systems, controlled application of elicitors can significantly increase the yield of desired compounds without the need for large-scale cultivation. This approach is particularly useful for producing rare or high-value phytochemicals used in pharmaceuticals and nutraceuticals. In addition to increasing metabolite production, elicitors can also improve the quality and bioactivity of plant-derived compounds. For instance, elicitor-treated plants often exhibit higher antioxidant activity and enhanced therapeutic properties. This has important implications for the development of functional foods and herbal medicines. Another important aspect is the role of elicitors in stress adaptation. Secondary metabolites often function as protective agents that help plants cope with environmental stress. By enhancing their production, elicitors contribute to improved stress tolerance and overall plant fitness. Despite their benefits, the use of elicitors in metabolite production requires careful optimization. Factors such as concentration, timing, and method of application can significantly influence the outcome. Therefore, a thorough understanding of elicitor-plant interactions is essential for

maximizing their potential, elicitors are powerful tools for enhancing secondary metabolite production in plants. Their ability to stimulate biosynthetic pathways and improve compound quality makes them valuable for both agricultural and industrial applications.

8. Future Perspectives

Advancements in biotechnology and molecular biology are rapidly expanding the scope and application of elicitors in plant defense and crop improvement. Modern “omics” technologies—including genomics, transcriptomics, proteomics, and metabolomics—have enabled a deeper understanding of plant-elicitor interactions at the molecular level. These approaches allow researchers to identify key genes, proteins, and metabolic pathways involved in elicitor-induced responses, thereby facilitating the discovery of novel elicitors and their precise mechanisms of action. High-throughput sequencing and bioinformatics tools are particularly valuable in uncovering regulatory networks that govern plant immunity. Genetic engineering and genome-editing technologies, such as CRISPR/Cas systems, offer promising opportunities to enhance plant responsiveness to elicitors. By modifying genes involved in receptor recognition, signal transduction, or defense pathways, it is possible to develop crops with improved resistance to pathogens and environmental stresses. Additionally, synthetic biology approaches can be employed to design customized elicitor molecules with enhanced specificity and efficiency. Nanotechnology is another emerging field that holds significant potential for elicitor delivery. Nano-formulations can improve the stability, bioavailability, and targeted delivery of elicitors, ensuring controlled release and increased effectiveness. This approach can minimize the quantity required and reduce environmental impact. Furthermore, integration with precision agriculture technologies—such as sensors, drones, and data analytics—can enable site-specific application of elicitors, optimizing their use under field conditions. Despite these advancements, challenges such as variability in plant responses, environmental influences, and cost-effectiveness need to be addressed. Future research should focus on field validation, formulation development, and understanding cross-talk between signalling pathways. Overall, integrating elicitor-based strategies with conventional and modern agricultural practices offers a promising pathway toward sustainable and resilient crop production systems.

9. Conclusion

Elicitors play a fundamental role in activating plant defense mechanisms and enhancing resistance against a wide range of biotic and abiotic stresses. By serving as signalling molecules, they initiate complex networks of perception, signal transduction, and gene expression that ultimately lead to effective defense responses. These responses include the production of antimicrobial compounds, activation of defense-related proteins, reinforcement of plant cell structures, and induction of systemic resistance throughout the plant. One of the most significant advantages of elicitors is their eco-friendly nature. Unlike conventional chemical pesticides, elicitors do not directly target pathogens but instead strengthen the plant’s inherent defense system. This reduces the risk of environmental pollution, development of resistant pathogen strains, and harmful effects on non-target organisms. As a result, elicitors represent a sustainable

alternative for crop protection in modern agriculture. Furthermore, elicitors contribute to enhanced production of secondary metabolites, improved plant health, and increased crop productivity. Their application is not limited to disease resistance but also extends to stress tolerance and quality improvement of agricultural produce. However, successful implementation requires a thorough understanding of their mechanisms, optimal concentrations, and application methods, the integration of elicitor-based approaches with advanced technologies and sustainable farming practices holds great promise for the future of agriculture.

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