Chapter 1
Introduction: Impact of Nanotechnology on Plant Cell Biology

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Abstract This book focuses on the recent progress of nanotechnology, emphasizing the interaction between nanoparticles (NPs) and plants at the cellular level. Furthermore, it covers understanding of pathways of nanomaterials (NMs) entry into plant cells, their influence on cellular organelle processes, and their influence on total crop yield. It includes 17 chapters, grouped in three sections: (1) Cellular mechanisms, (2) Cellular macromolecules, and (3) Implications of NMs. These chapters provide details on plant response to NMs applications including morphological, physico-chemical, and anatomical changes and their effect on plant growth and productivity. The mechanisms of absorbance and translocation of NPs and their interaction with the plant cellular biochemical compounds and organelles are also covered. This book describes the current perspective of NMs' influence on cellular processes including photosynthesis and pigment synthesis and accumulation. Also highlights the current understanding of the impact of NMs on cellular macromolecules, these processes and biochemical compounds have implications for crop yield.

Keywords Adsorption · Cellular macromolecules · Cellular mechanisms · Cell biology · Plant nanotechnology

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1.1 Introduction

Nanotechnology contributes novel tools to impact and enhance crop production and provide an alternative approach for crop improvement. Nanomaterials (NMs) interact with various cellular macromolecules leading to both negative and positive effects, especially the enhancement of plant growth and resistance to different stresses. NMs optimize plant water and nutrient conditions, improving production quality and quantity. On the other hand, NPs are toxic to plant growth and human health via the food chain (Minkina et al. 2020).

The NPs gather in cell walls, tissues, and sub-cellular organelles such as chloroplasts and vacuoles, resulting in decreasing biological activity such as photosynthesis and metabolism in plant cells, reducing the germination rate and decreasing the length of root and shoot. They promote oxidative stress, antioxidant, nutritional imbalance for edible crops and quality of productivity. NPs in plant tissues have an impact on physiological processes (as promote or inhibit) and on the safety of macromolecules and cell organelles (Fedorenko et al. 2020).

There are essential factors related to the NPs and their interaction with plant tissues such as the plant species involved, which have physiological and anatomical differences, chemical characteristics of the plant's cellular surface, also environmental conditions surrounding it (Minkina et al. 2020).

1.2 Cellular Mechanisms

This section describes the interaction of NPs in different parts of plants (roots, shoots and leaves) at the cell organelles level (Fig. 1.1).

1.2.1 Adsorption

The first step is to absorb NPs via the roots and distribute it to plant tissues through modifications such as crystalline dissolution, biomodification and bioaccumulation. Plant roots and plant growth tissues are therefore the primary hosts for receiving NPs (Rao and Shekhawat 2016).

A variety of factors influence the absorption of NMs, including nanomaterial features, plant physiology, application method and environmental conditions.

NMs can interact with microorganisms and soil compounds that can positively or negatively modify absorption efficiency according to the type of NMs. Furthermore, multiple tissues (epidermis, endodermis) and barriers (Casparian strip, cuticle) need to be crossed before reaching vascular tissues, according to the entry point (roots or leaves) (Rajput et al. 2018).

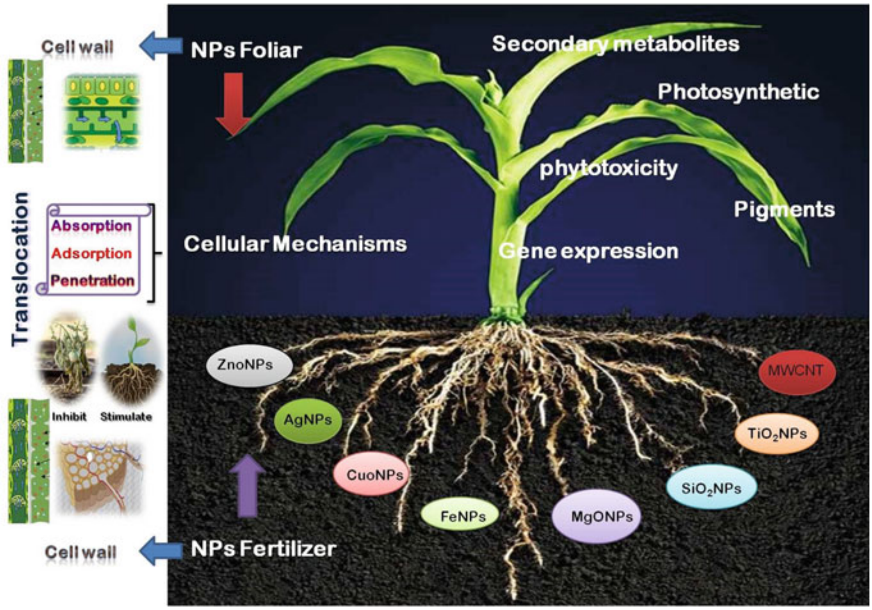

Fig. 1.1 The impact of nanotechnology on plant cellular mechanisms (Constructed by L.M. Alnaddaf)

1.2.2 Penetration

The pathway of NMs to penetrate and uptake inside the cell can be via many ways, such as pore formation: Some NMs may disturb the plasma membrane, causing pore formation to pass via the cell; ion channels: These channels are about 1 nm in size, making it highly unlikely that NMs will penetrate them effectively without significant modifications; carrier proteins: NMs may bind to cell membrane proteins which act as carriers for entry into the cell; endocytosis: The NMs are embedded in the cell as a vesicle which may move in various compartments of the cell; and plasmodesmata (Schwab et al. 2016).

1.2.3 Cell Wall

NPs mainly modify the chemical composition and physical parameters of the cell wall affecting its structure. This modification is related to some factors such as the rate of pectins, structural proteins and phenolic compounds, cellulose, and hemicellulose. Also, pH, cell-wall existing enzymes, and acid cell wall properties regulate its porosity (Milewska-Hendel et al. 2017).

There are some characteristics NPs possessed that allow them to pass through cell walls such as size, shape, dimensions, The surface charge of NPs, composition, concentrations, the amount of fertilizer used, plant species, and conditions of the environment. The interaction between NPs and plants, whether stimulating or inhibiting, varies according to the previous characteristics (Milewska-Hendel et al. 2021).

1.2.4 Translocation

NMs move via plant tissue in the apoplast and the symplast. Also, the importance of the way NMs move inside plants gives indications about where they reach, end and accumulate (Milewska-Hendel et al. 2021).

This book presents several examples of translocation and accumulation of NPs in plant tissues, whether applied as soaked grains, fertilizers and foliar applications. For instance, NMs of carbon-coated iron are transferred to the aerial parts in pea and wheat faster than in sunflower and tomato (Perez-de-Luque 2017).

Also, this process is related to the size of the material and the zeta potential when carbon dots as a model is used in the translocation via the leaves in corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.). Moreover, FeONPs penetrate the roots in (*Cucurbita pepo* L.) and accumulate in the roots' cells without transferring to leaves or flowers due to NPs magnetic properties (Tombuloglu et al. 2020).

1.2.5 Photosynthetic

A nanotechnology is a feasible tool for optimizing photosynthesis. It is related to primary metabolism and is responsible for generating plant biomass. Also induces plant growth and development (Sáez et al. 2017).

The effectiveness of NPs on photosynthetic (enhancing or impeding) and the functionalities of photosynthetic elements vary according to different plant species. This effect appears via an effect on regulatory proteins of the thylakoids, photosynthetic pigment (chlorophyll a and b), the activity of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo), carbon dioxide aggregation, adequate grana development and structural stability of mesophyll cells as well as chloroplasts (Kataria et al. 2019).

The enhancing or impeding influences of NPs on photosynthesis and plant growth are varied depending on nonmetallic NPs or metallic NPs. The stimulated reactions of nonmetallic NPs of photosynthesis are generated by biocompatible and reducing the oxidation processes. Also, NPs can be exploited for harvesting more electrons, which in turn, enhancement of plant photosynthesis and increases biomass and crop productivity (Swift et al. 2019).

Conversely, metallic NPs had impeding photosynthesis, which harmfully affects the different photosynthetic mechanisms. Impeding effects can be summed up for

NPs on the photosynthetic as toxicity via production of ROS and reduction each of the following: the net photosynthesis, chlorophyll content, photosystem II activities, the number of thylakoids per grana, the transpiration rate, leaf stomatal conductance, intercellular carbon dioxide concentration rate as well as inhibiting the expression of genes each of photosystem structure and chlorophyll biosynthesis (Poddar et al. 2020). These effects appeared via an application of different types of NPs, such as walled carbon nanotubes (SWCNTs), iron oxide, silver NPs, TiO_2 NPs, CuO NPs, ZnO NPs, carbon dots, Al_2O_3 NPs, Si NPs, Se NPs, Superparamagnetic iron oxide nanoparticles (SPION) for a variety of plant species (Kataria et al. 2019).

Carbon-based NMs interact with accessory pigments in the chloroplasts and chlorophyll-a, and chlorophyll-b and promote the ability of plants to harvest light energy. Whereas, NPs used as artificial antennae permit chloroplasts to absorb wavelengths that aren't essential for photosynthesis. This enhances the ability of plants to interact with light and optimize its capture, which increases the productivity of crops and enables the plants to adapt to different environments, where there is extremely solar radiation or limited resource of light (Aguirre-Becerra et al. 2020).

1.2.6 Pigments

NPs interact with plant pigments (Chlorophyll and derivatives, Carotenoids, Anthocyanins, and Betalains). Once it penetrates the plant chloroplast then the attachment occurs between NMs and pigments plant, which acts as cell protection agents, light-harvesting complexes, transfers absorbed light energy to chlorophyll molecules, dissipates excess energy to the environment and as antioxidant molecules when stress occurs (Nguyen et al. 2021).

Comprehension of the interaction mechanisms of NMs with plant pigments is critical to know its possible side effects on the biochemistry, metabolism, and physiology of plant organisms when NMs are absorbed. The plant produces more than 200,000 different chemical compound types including colored (pigment) compounds (Tripathi et al. 2020).

Engineered NMs interact differently with plant pigments depending on pigment type and their physical-chemical properties resulting in two various basic responses: the first is the pigment content (increase/decrease) by (promoting/inhibiting) the pigment synthesis. The second change is the pigment activities, especially energy dissipation processes and light absorption. Most of the literature indicated that plants respond to different types of NPs by reducing chlorophyll content followed by increasing the accessory pigment's contents. Thus, any functional or structural modifications in plant pigments, especially photosynthetic ones, affect the photosynthetic performance and biomass productivity (Nguyen et al. 2021).

NPs interact with plants to know about the implications of NMs on the plant morphological, physiological, production responses, and biological phenomena, to promote absorption of light wavelengths and optimize its capture and enhance photosynthesis (Santiago et al. 2020).

There are many factors that affect the content of the pigment in plant cells. For instance, biotic and abiotic stress induce the generation of reactive oxygen species (ROS) which increase the expression of genes involved in the pigment biosynthesis pathway, the synthesis route of NMs (green or chemically synthesized) and the usage dose (Tripathi et al. 2020).

1.2.7 Secondary Metabolites

NMs play an essential vital Role in plant cell and tissue culture. NPs have stimulated the biosynthesized secondary metabolites and gene expression for it (Wang et al. 2021).

NPs promote secondary metabolites (for instance, flavonoids, phenolic acids, glucosinolates, terpenoids, and alkaloid compounds). These play an antioxidant activity to enhance plant growth under biotic and abiotic stresses. As well as it decreases drought-induced damage such as *Z. mays* L., improves the quality of fruits under drought stress for *P. granatum* and increases yield. Also, the pharmacological properties of several medicinal plants are imputed to secondary metabolism compounds. Therefore, any change in bioactive compounds by NPs could affect their pharmacological properties and market importance (Ma et al. 2020).

Once the cells absorb the NMs, the metal-base of the NMs is turned into reactive metal ions, which react with functional groups present in a cell leading to a change in their biochemical activity. These interactions are various depending on plant species and tissues, size, solubility, concentration, shape, thermodynamic properties, composition, and surface coating. The main indicators resulting in NMs toxicity in the plant are the reduction of photosynthetic processes and the generation of ROS (Zahedi et al. 2021).

1.2.8 Phytotoxicity

The phytotoxicity caused by NPs is usually triggered by the release of free radicals such as hydrogen peroxide and hydroxyl radical. The excessive production of ROS interacts with various biological molecules and causes different cellular damage. It can also increase the level of oxidative stress, the fragmentation of peptide chains and alter the electric charge. Furthermore, it increases the susceptibility of various proteins to proteolysis, DNA and cell membrane damage, the toxicity of carbon-based NMs, the toxicity of metal and metal oxide NMs and anatomical and morphological changes (Kolenčík et al. 2021).

Exposure to NPs lead to adverse effects on several biochemical and physiological processes in different plant species which affects the growth stages of plants. Also, accumulated NMs in different plant parts can affect human health. In the contrast, some studies have indicated that not all plants treated with NMs demonstrated toxic effects (Tombuloglu et al. 2020).

1.2.9 Gene Expression

In plants, numerous alterations resulting treated with NMs observed in genetic (DNA mutations) and epigenetic (DNA methylation pattern, histone modifications, and RNA interference). They were reflected in many aspects of the plant growth and development, such as cell divisions, chromosome behavior, mitotic aberrations, DNA alterations, and gene regulation related to forming the cell wall, roots, leaves, stress, and water channels (Khan et al. 2019).

SWCNT inhibited histone H3K9 acetylation in Maize seed's response to drought stress. Applying carbon nanotubes (CNT) in *Solanum lycopersicum* L. leads to the downregulation of genes related to roots and leaves. In contrast, increasing the upregulation of genes is related to water channels and stress (LeAqp2). In addition, Multiwalled carbon nanotube (MWCNT) had an impact on the upregulation of marker genes NNtPIP1, NtLRX1, and CycB, related to the formation of cell divisions and the cell wall (Khan 2020).

1.3 Cellular Macromolecules

Carbohydrates, nucleic acid, hormones, proteins, enzymes, and lipids are the main components of plants. These compounds contributed to NPs synthesizing as a safe and eco-friendly method. Also, they are closely associated with stress tolerance, growth and development of plants via increasing or decreasing their percentage when applying several NPs to plants (Khan et al. 2021).

1.3.1 Carbohydrates and Lipids

The chapter on the interaction of NPs with plant macromolecules: carbohydrates and lipids summarizes recent advances in the different effects of NPs to promote or inhibit plant growth, such as seed germination, plant root, and above-ground growth and improve various stress tolerance, which is closely associated with plant carbohydrates and lipids (Shang et al. 2019).

This stimulating or inhibiting is occurring using various types of NPs, for example, silver, selenium, zinc oxide, copper oxide, magnesium oxide, and silicon dioxide in different stages of growth and development of a plant. In addition, this chapter

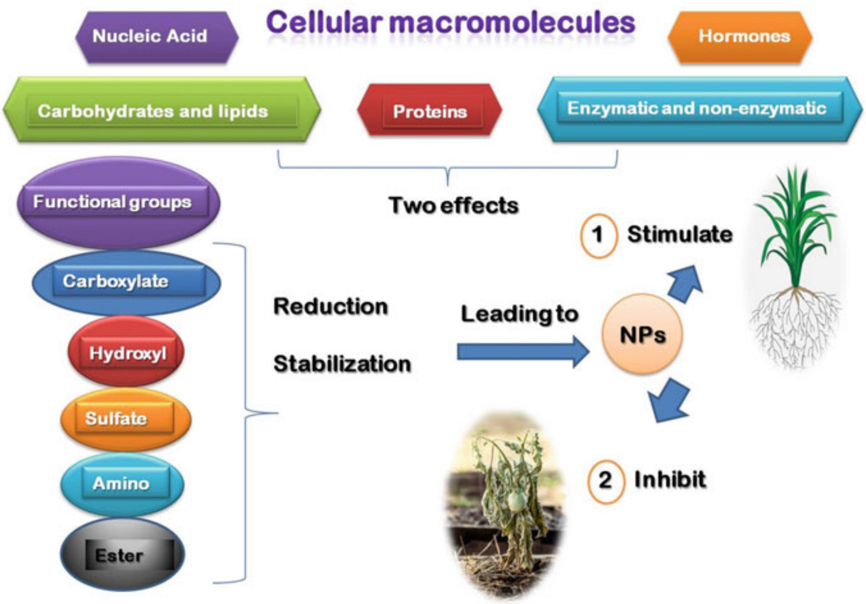

Fig. 1.2 The impact of nanotechnology on cellular macromolecules (Constructed by L.M. Alnaddaf)

discusses the different effects of NPs added as a spray or fertilizer on morphological, biochemical, and productivity indicators of various plants (Khan et al. 2021) (Fig. 1.2).

1.3.2 Nucleic Acid

All genetic information for every living entity exists in nucleic acids (DNA and RNA) (Tan et al. 2009). This book presents a chapter to introduce the NPs interaction with nucleic acids. This interaction relates to type of NPs and concentrations.

In addition, it can use as delivery system DNA and RNA by binding interactions such as carbon nanotubes and bioclay (Hossain et al. 2016). Also, explains in more details the different effects either positive (activate the genes related to stresses) or negative (chromatin condensation and cells shrinkage, damaged DNA, fragmentation of chromosome arms and suppressing transcriptional genes) (Chen et al. 2018).

1.3.3 Hormones

There are five types of hormones that exist naturally in plants: auxin, cytokinin, gibberellins, abscisic acid and ethylene (Gaspar et al. 1996). NPs enhance the various physiological activities of hormones in plants (Weyers and Paterson, 2001). These activities relate to growth (elongation of roots or shoots), maturation, plant tissue culture and biotic or abiotic stress responses in a plant (Yang et al. 2017). While, other side effects are linked to senescence or phytotoxicity (El-Shetehy et al. 2020).

1.3.4 Proteins

Proteins are necessary for all living cells and have several functions such as regulation, cell signaling, catalysis, support, membrane fusion, intra- and intercellular movement of nutrients and other molecules, and structural protection. When NMs penetrate into plant cells, it reacts with carboxyl and sulfhydryl groups and alters protein activity (Anjum et al. 2015).

The NMs reaction depends on the physical and chemical conditions of the cell environment, which is affected by reactive molecules, and temperatures.Also, its sizes and concentrations affect the folding process of a newly synthesized protein (Hossain et al. 2016).

The plant responds to NMs treatment via several indicators such as an increase or decrease in proteins, accumulation or synthesis of new types of proteins that are involved in primary metabolism and production of enzymes that help the metabolic adaptation of the plant. In addition, Increasing proteins -are related to photosynthesis, metabolism, cellular organization, and hormone metabolism (Fig. 1.2) (Hasan et al. 2017).

1.3.5 Enzymatic and Non-Enzymatic Antioxidant

The influence of NMs on enzymatic antioxidant defense activities in plants differs according to the nature and concentration of NPs.

There is a regulatory suitable balance between ROS and antioxidants (enzymatic and non-enzymatic) in natural conditions. However, the plant responds with an increased amount of ROS concentration in conjunction with antioxidants when NPs stress occurs in the plant (Shang et al. 2019).

Antioxidants break down the ROS and scavenge it due to their peculiar structures and detoxify cells, such as oxygen free radicals and lipid peroxidation radicals.

In various researches, the impact of NPs on plant growth was different between promoting and inhibiting (Fig. 1.2) (Khalil et al. 2020).

1.4 Preparation and Features of NM

This book presents the methods to synthesize NM, such as physical, chemical and biological manufacture. Each method has a different feature that is related to its application (Alnaddaf et al. 2021). In addition, emphasizes the advantages of biosynthesis of monometallic NPs and includes some examples of silver, gold, copper, palladium and oxide NPs. Also, explains the factors that affect the NMs traits and behavior which make them able to penetrate plant cells (Shekhawat et al. 2021).

1.4.1 Nanocellulose

Cellulose is a natural polymer derived from agricultural waste and by-products used for the synthesis of various kinds of NMs. This chapter converses the synthesis of nanocellulose. Then, explains in more detail the source, structure, and types of nanocellulose. Also, it highlights the preparation, characterization, and properties of nanocellulose. In addition, it discusses the application of nanocellulose in many sectors (Zhang et al. 2022).

1.4.2 2D-Nanosheets

A chapter presents the 2D-nanosheets based hybrid NMs interaction with the plants. In addition, explains the different methods of synthesis of 2D-nanosheets. Then, emphasizes the interaction of 2D-nanosheets with plants. Moreover, it also highlights to penetration of 2D-nanosheets the seed coats, translocation in the plants and effects on plant growth and development (Lee et al. 2021).

1.5 Implications of Nanomaterials on Crop

The plant has different responses to treatment with NPs, whether morphology physiology and productivity (Hossain et al. 2020) (Fig. 1.3).

This book highlights the mechanism of NPs interaction in seed and various effects on seed germination and root growth, shoots, leaves, flowers and fruits. In addition, this book includes examples of many types of NPs. Also, their role to improve crop productivity by mentioning features of NPs in crop quality and quantity improvement (Rivero-Montejo et al. 2021).

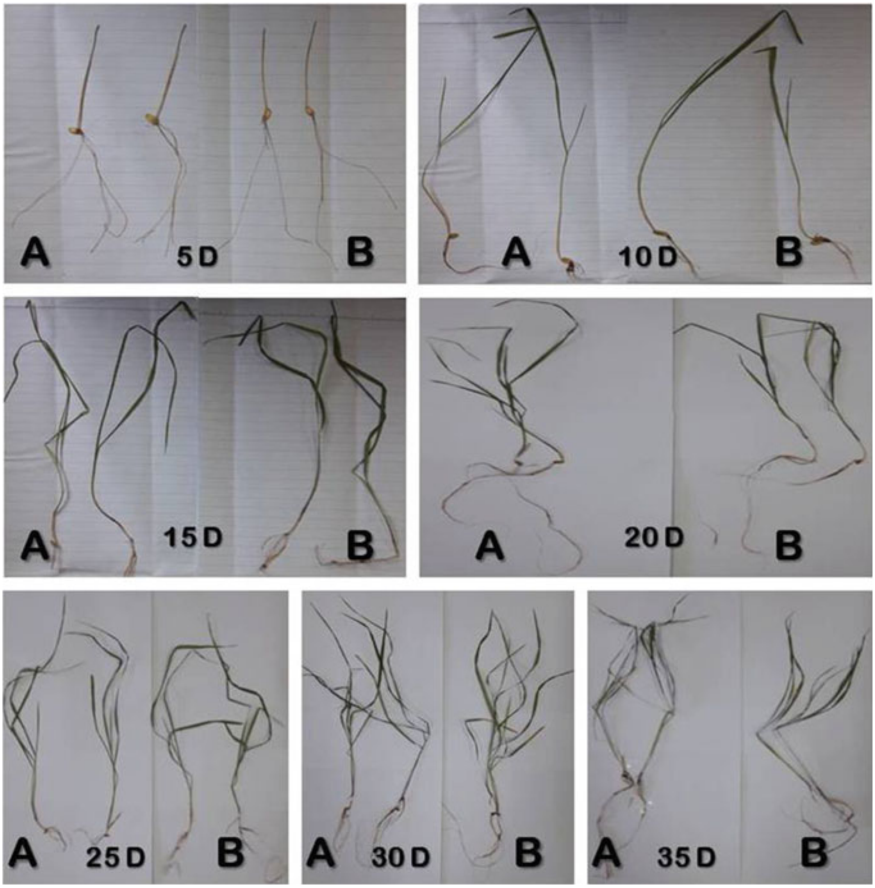

Fig. 1.3 The impact of AgNPs on wheat seedling morphology during 35 days. A: treatment with AgNPs, B: control, D: day (Constructed by L.M. Alnaddaf)

1.5.1 Nutritional Value

The future goals of nanotechnology include high bioactive compound content of secondary metabolites in foods which advantages in improving the nutritional value of industrial crops and stress tolerance (Neme et al. 2021). Plants consider an essential component of the human diet via the supply to our body of vitamins, proteins, minerals, fiber, carbohydrates, lipids, and water (Rivero-Montejo et al. 2021).

The use of NMs has improved the nutritional value of fruits and vegetables without requiring increased consumption by affecting the biochemical and physiological properties of plants (Gomez et al. 2021).

1.5.2 Abiotic Stresses

The soil salinity, water's decrease, and heavy metal increase are the most dangerous to a plant's life cycle which knows as abiotic stresses (Gong et al. 2020).

Stresses adversely affect the plant growth and development via changes in the structural and chemical composition of the plant which lead decreasing in quality and quantity of production. Plants have developed various mechanisms to tolerate these challenges via transferring the stress signals within cells and between cells and tissues, sorting suitable chemical compounds for survival and reproduction, and continuing their growth and development (Rivero-Montejo et al. 2021).

Many reports indicated that when plants are treated with NPs their responses to stresses will be various via influence on biological and metabolism pathways. Also, their role to improve crop tolerance to abiotic stress for instance drought, salinity, and heavy metal stresses (Zohra et al. 2021).

1.5.3 Tissue Culture

A chapter is included to discuss the role of NMs in plant cell and tissue culture. It explains the impact of NMs on in vitro responses. Different NPs in tissue culture media could improve the callus induction, biomass and morphogenetic potential in explants (Barbasz et al. 2016).

NPs play a vital role in various biochemicals, physiological and anatomical routes of tissue culture. NPs improve regeneration, organogenesis, decontamination and secondary metabolite production to protect plant cells and tissues from biotic and abiotic stress. NPs have affected nutrient and protein levels and modulate the expression of certain genes encoded in certain proteins. In addition, it highlights the mechanism affecting callus, and quantitative and qualitative features of calli (Dallavalle et al. 2015).

In addition, it presents an overview of some important applications of NMs in plant tissue cultures such as somaclonal variation, organogenesis, somatic embryogenesis, disinfection, genetic fidelity, and regeneration (Devasia et al. 2020).

1.6 Conclusions and Prospects

This book provides an update on research and development in plant nanotechnology. It covers comprehensively various methods to synthesize NM and its characterization and applications. Moreover, explains the interaction of the NPs with plant cellular mechanisms and macromolecules. The initial phase is interacting NPs with the plant surface lead to adsorption it from the root and penetrate cell wall to move in plants. The second phase begins from the series of different effects at various levels, such as the molecular, biochemical, physiological, morphological and productivity, which it reflects stimulating or inhibiting on the growth and development of the plant.

In addition, the book highlights the implications of NPs in different stages of plant growth and their effect on decreasing or increasing the quality and quantity of production as well as application in tolerating various stresses. Moreover, the book presents the role of NPs in tissue culture and their impacts on the callus physiology, biomass of explants and secondary metabolites according to the type of NPs and their concentrations.

Hence, future research needs to understand the mechanical complexity of interactions NPs with the plant (uptake, translocate, and accumulation) in different parts of a plant. Also discussed in details their effect of different NPs on growth stages in various plant species at the cellular levels.

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