Chapter 11
2D-Nanosheets Based Hybrid Nanomaterials Interaction with Plants

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Abstract Agricultural growth needs a newer policy that speeds up plant growth and the nutritional value of the crops. Numerous agrochemicals, pesticides, and fertilizers provide nutrients to crops and enhance plant growth and nutrition quality. However, the demand for food remains a concern. In this context, 2D-nanomaterials or nanosheets have the potential ability to overcome issues associated with agrochemicals. 2D-nanosheets easily penetrate the seed coats and translocate with the plants using apoplastic and symplastic pathways. The high translocation ability regulates various molecular and biochemical pathways, thereby improving plant growth and development. However, a higher dose of the 2D-nanosheets shows the phytotoxic effects by increasing the production of reactive oxygen species. In this context, 2D-nanosheets-based hybrid materials might be beneficial for improved plant growth with minimal phytotoxicity. Moreover, 2D-nanosheets-based hybrid materials also protect crops against various pathogenic microorganisms. This book

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chapter focuses on synthesizing 2D-nanosheets, 2D-nanosheets-based hybrid materials, and their interaction with the plants. We also discuss the effect of 2D-nanosheets and 2D-nanosheet-based hybrid materials for plant growth and the protection of crops.

Keywords Crop protection · Nanofertilizers · Plant growth · Translocation · 2D-nanosheets

11.1 Introduction

Presently, the fast population growth and changes in the weather/climate globally require effective crop cultivation practices that fulfill increasing food needs. Efficient crop cultivation processes are one of the significant challenges now-a-days. Agricultural growth requires a new platform to accelerate plant growth and crop nutrition quality. Moreover, several materials in the form of pesticides and fertilizers are used to provide protection and nutrients to crops for enhanced plant growth and nutrition. These chemicals manage phytohormones levels within the plants that improve plant growth, crop yield, and the nutritional quality of grains. However, excessive use of agrochemicals decreases soil fertility and adversely affect the environment. Additionally, these chemicals accumulate in the plants and cause adverse effects to humans and animals health as well as negative impact on the environmental (Afreen et al. 2022b, 2022a; Ashfaq and Khan 2017; Chauhan et al. 2020; Sultana et al. 2022). To overcome these limitations, several nanomaterials have been synthesized and applied as nanofertilizers.

Nanomaterials (NMs) such as one-dimensional (1D) (carbon nanotubes (CNTs), carbon nanofibers (CNFs), metal-and metal-oxides), two-dimensional (2D) (graphene, graphene oxide (GO), and nanosheets of metal-and metal-oxide) nanomaterials have been used to augment plants growth. The 1D-nanomaterials like metal and metal-oxide (Cu, Zn, Fe, Ce, and Au) augmenting the growth of the plants. However, these metals and metal-oxides accumulate on the root surface causing less translocation ability and phytotoxicity (Ashfaq et al. 2022; Irsad et al. 2020; Kumar and Talreja 2019; Mustafa et al. 2011; Omar et al. 2019a, 2019b; Talreja and Kumar 2018). In this respect, carbon-based nanomaterials like CNTs, and CNFs are efficiently used in various applications, mainly antibiotics materials (Ashfaq et al. 2016), drug delivery (Ashfaq et al. 2014), environmental remediation [i.e., removal of heavy metals ions (Afreen et al. 2018; Khare et al. 2013; Kumar et al. 2011; Talreja et al. 2014), pharmaceuticals compounds (Saraswat et al. 2012; Talreja et al. 2016), and microorganism from water (Singh et al. 2013)], sensor (Ashfaq et al. 2018; Kumar and Talreja 2019), wound dressing (Ashfaq et al. 2017b; Bhadauriya et al. 2018), nanomedicine (Madani et al. 2011) and agriculture (Ashfaq et al. 2017a; Kumar et al. 2018). The CNTs and CNFs have the potential ability to penetrate seed coats, thereby efficiently translocate within the plants. The CNTs and CNFs also served as carriers for the agrochemicals or micronutrients, or fertilizers due to insignificant toxicity against both animal and plant cells (Ashfaq et al. 2013). Despite the tremendous success of the 1D materials, researchers continue focusing on the development of newer NMs that enhances the growth, development, and yield of the crops. In this aspect, 2D-nanomaterials have the potential ability to efficiently translocate within the plants and enhance the crops' growth and productivity. 2D-NMs are the newer class of material that has at least 1D in nanometer-sized. The 2D-NMs are widely used in several applications, including agricultural, energy storage, sensor, environmental decontamination, photocatalyst, biomedical, etc. due to their excellent property such as large surface area, feasible surface charge, high mobility in soil, biocompatibility makes it an ideal candidate (Ashfaq et al. 2021, 2022; Nag et al. 2018; Sasidharan et al. 2021, Sun et al. 2018, Tao et al. 2017; Wang et al. 2019; Ismail 2019; Zheng et al. 2021). One of the widely used members of this class is Graphene. Graphene was first exfoliated from graphite, a three-dimensional counterpart of graphene using the scotch tape method by Novoselov and Geim in 2004 (Cai et al. 2012); after that, several methods have been adopted to synthesize graphene. Few layered graphenes (FLG), ultrathin graphite, graphene oxide (GO), reduced graphene oxide (rGO), graphene oxide (GO), and graphene nanosheets (GNS) and their composites have been widely used in plant growth and development. Interestingly, these 2D-NMs like graphene and GO have translocation ability that easily penetrates seed coat due to the graphitic content and π-π electron. The higher translocation ability of the graphene and GO might be beneficial for the plants in various aspects, (1) increased the water uptake ability, (2) improved micronutrient delivery, (3) germination rate, (4) increased nutritional value of grains, and (5) plant growth and development. However, it seems difficult to used 2D-nanomaterials directly in the agricultural land due to handing that leads phytotoxicity. In this aspect, 2D-nanomaterials based hybrid materials might be resolved issues associated with 2D-nanomaterials.

Numerous polymers, such as polyvinyl alcohol (PVA), starch, cellulose, and chitosan, have been used to encapsulate 2D-NMs that efficiently delivered the agrochemicals or micronutrients or fertilizers (Sampathkumar et al. 2020; Sikder et al. 2021). These polymers aided various advantages like the controlled release of micronutrients or fertilizers or agrochemicals, increased soil nourishments, improved photosynthesis, water uptake capacity, and biocompatibility of the 2D-NMs. Herein, we discuss the synthesis of 2D-NMs, the interaction of 2D-NMs with plants, the role of 2D-NMs in the growth and development of plants, and the role of 2D-NMs based hybrid materials for plant growth. We also discuss the toxicity and prospects of 2D-nanosheets-based hybrid materials in agriculture.

11.2 Synthesis of 2D-Nanosheets

Recently, the synthesis of high-quality atomically thin 2D-NMs is attracting research interest as large areas and crystal quality enables the integration of optical and electronic devices with improved efficiency. Several challenges have to be overcome while synthesizing 2D material, such as thickness control, defects, size, crystal quality, and disorders; otherwise, detrimental consequences have been observed during device performances. Various synthetic approaches, including top-down and bottom-up, have been adopted to overcome these challenges, such as non-uniformity and defects in 2D crystals, which subsequently affect device performance (Han et al. 2015; Zavabeti et al. 2020). These methods have divided as follows.

11.2.1 Top Up Approach for the Synthesis of 2D-Nanosheets

The most widely used exfoliation techniques are part of the top-up approach. Exfoliations are of two types (1) liquid phase and (2) mechanical exfoliation. Liquid exfoliation is a straightforward, low cost and simple method. Nanosheets can be synthesized by placing the bulk materials into appropriate solvent and using sonication for some hrs. Solvent selection is one of the essential parts of liquid phase exfoliation is. The surface energy of solvent should be matched with the Vander wall interaction of nanosheet, which can improve the quality of exfoliation. Several kinds of literature use liquid-phase exfoliation to synthesize nanosheets, such as León-Alcaide et al. (2020) utilized the liquid-phase exfoliation method to separate Fe-based magnetic MOFs MUV-1-X, having a lateral dimension of 8 μm and thicknesses of 4 nm. The author observed nanosheets retain their structural integrity and magnetic properties. Huang et al. (2017) exfoliated SnSe nanosheet using liquid-phase exfoliation and the synthesized nanosheet is of high quality and can be utilized in photoelectronic applications (Huang et al. 2017). These studies suggest that liquid-phase exfoliation can be widely used. However, liquid-phase exfoliation also has several disadvantages, such as lower crystal quality and low yield limits its practical application (Huo et al. 2015). Figure 11.1 shows the schematic representation of the liquid exfoliation process.

11.2.2 Mechanical Exfoliation of 2D-Nanosheet

Novoselov et al. (2004) for the time used mechanical exfoliation to exfoliate graphene from graphite using scotch tape. After that, several 2D materials were synthesized using mechanical exfoliation. This method synthesizes high-quality 2D material with fewer defects and better crystal structure and controllability in patterned transfer. Huang et al. (2020) used Au-assisted mechanical exfoliation method and synthesized single-crystal nanosheet with high-quality crystal. He further made a theoretical study to confirm the method's applicability. Li et al. (2018) utilized mechanical exfoliation to exfoliate 2D perovskite microplates. The synthesized 20 nm thick nanosheet can be applied as electrodes for photodetection (Li et al. 2018).

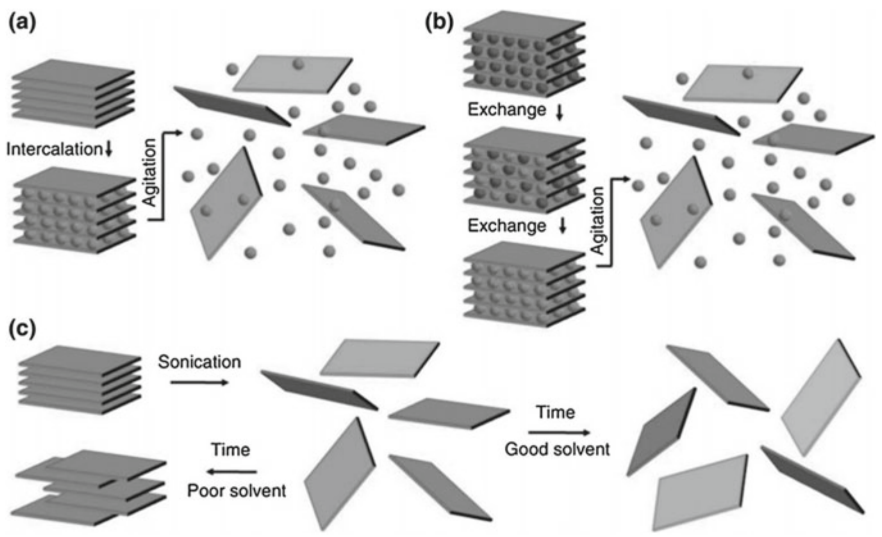

Fig. 11.1 Schematically illustration of the liquid exfoliation process, **a** by ions intercalation, **b** by ions exchange, and **c** by sonication. The figure was reproduced with permission (Huo et al. 2015)

11.2.3 Bottom-Up Method for Synthesis of 2D-Nanosheet

Chemical vapor deposition (CVD) is a potential method to grow nanosheets on various substrates such as nickel form, Cu foil, Activated carbon fabric, etc. The technique involves the decomposition of precursors on the substrate at high temperatures. This method synthesizes high-quality crystal, scalable size, tunable thickness, and excellent electronic properties with the effortless operation, which is considered an industrial-grade method. However, several parameters need to consider to achieve higher growth, such as temperature, pressure, flow rate, precursor gas, and substrate. Several researchers reported that there should be a balance between reactive gas and material (Okada et al. 2019; Seravalli and Bosi 2021; Zhang 2015). The CVD method was used to synthesize high-quality nanosheets, including the synthesize of $MoSe_2$ crystals on molten glass using CVD process within 5 min to achieve a triangular monolayer with lateral size of 2.5 mm and having carrier mobility up to ~95 $cm^2/(V\cdot s)$ (Chen et al. 2017). Another study synthesized a high-quality monolayer of WS_2 on a SiO_2/Si substrate using the CVD processsynthesized triangle domain of high crystal quality with 52 μm (Fu et al. 2015). Yan et al. synthesized HfS_2 flakes using the CVD process with a lateral size of 5 μm and thickness of 1.5 nm having hexagonal structure (Yan et al. 2017).

11.3 Interaction of 2D-Nanosheets with Plants

Usually, NMs or 2D-nanosheets easily penetrate the seed coats and translocate with the plants using two pathways, (1) Apoplastic pathway, which takes place outside of the plasma membrane (using cell-wall, extracellular spaces, and xylem vessels), and (2) Symplastic pathway, which take place within the cytoplasm (using plasmodesmata). Understanding the NMs or 2D-nanosheets translocation pathways within the plant is essential to indicate the accumulation or translocation path (Chichiriccò and Poma 2015; Sanzari et al. 2019a, 2019b; Su et al. 2019). The NMs or 2D-nanosheets are translocated within the plants through the xylem, indicating the translocation from root to shoot to leaf. In other words, NMs or 2D-nanosheets should be applied to the roots for better translocation. Whereas NMs or 2D-nanosheets show effective translocation through the phloem, indicating the foliar applications or downwards. In other words, NMs or 2D-nanosheets accumulate on the plant's fruits or grains. Moreover, translocation of the NMs or 2D-nanosheets is not limited to a specific cell (Cifuentes et al. 2010; Jeevanandam et al. 2018; Lin and Xing 2008; Spielman-Sun et al. 2019). The morphology and surface property of the NMs or 2D-nanosheets is mainly influenced the translocation ability. There are predominantly two characteristics is essential for the translocation of any NMs or 2D-nanosheets, (1) size of the NMs or 2D-nanosheets, up to 1 μm length of the NMs or 2D-nanosheets easily translocate within the plants. The nano-sized materials easily translocate within the plants through apoplastic and symplastic pathways. The NMs less than 50 nm in size easily translocate through the plasmodesmata. In contrast, larger size or more than 50 nm translocate through cell-wall, and (2) surface charge of the NMs or 2D-nanosheets, if the surface charge of the NMs or 2D-nanosheets is negative, so the negatively charged NMs or 2D-nanosheets interact with negatively charged plant cells, thereby NMs or 2D-nanosheets easily translocate within the plants through root to shoot to leaf due to strong repulsion force. On the other hand, if NMs or 2D-nanosheets are positively charged interact with negatively charged plants, thereby higher accumulation onto the root surface or less translocation ability due to solid attraction force (Ashfaq et al. 2017a; Kumar et al. 2018; Pérez-de-Luque 2017; Sultana et al. 2021). Figure 11.2 shows the translocation of the NMs or 2D-nanosheets within the plants through apoplastic and symplastic pathways. In general, smaller size and negatively charged NMs or 2D-nanosheets might be beneficial for practical translocation ability. Moreover, with the help of a functional group, we can easily modify the surface charge of the NMs or 2D-nanosheets. The higher translocation ability of the or 2D-nanosheets efficiently enhanced the plant growth, development, and yield of the crops by increasing protein content, chlorophyll content, root-shoot length, germination rate, and water uptake ability.

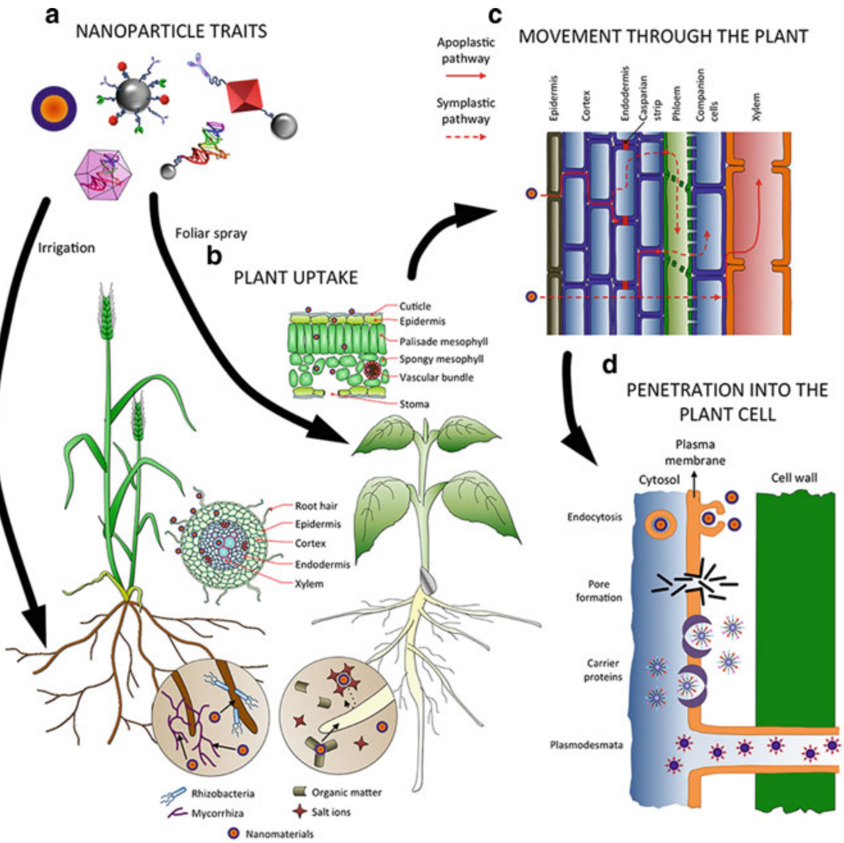

Fig. 11.2 Translocation of the NMs or 2D-nanosheets within the plants through apoplastic and symplastic pathways. The figure was reproduced with permission (Pérez-de-Luque 2017)

11.4 2D-Nanosheets for Plant Growth

The 2D-nanosheets research and development facilitate the next-generation delivery of micronutrients, agrochemicals, fertilizers, or pesticides within the plants. With the help of NMs or 2D-nanosheets, the plant's growth easily improved by enhancing water uptake capacity, chlorophyll content, protein content, and translocation ability of the micro-nutrients. These 2D-nanosheets extensively used in drug delivery, sensor, nanomedicine, environmental remediation, energy, and agricultural applications due to their exceptional characteristics (Aïssa et al. 2015; Carvalho et al. 2021; Choi et al. 2010; Dhinakaran et al. 2020; Hu and Zhou 2014; Mbayachi et al. 2021). Numerous 2D-nanosheets, especially graphene and graphene oxide (GO), have been used to augment plant growth. For example, Zhang et al. (2015) tested graphene against tomato seed and suggested that it has the potential ability to penetrate the seed coat; thereby, translocation was effectively observed. Moreover, the higher translocation ability of the graphene increased germination rate and seedling growth. The study suggested that graphene's remarkable translocation ability makes it a potential candidate for agricultural application (Zhang et al. 2015). Zhang et al. used graphene and tested it against wheat plants to determine graphene's toxic effects at higher concentrations. The data suggested that graphene shows the toxic effect at higher doses that induced oxidative stress, decreased chlorophyll content, and photosynthesis (Zhang et al. 2016). He et al. used GO and tested against spinach seeds. The data suggested that the GO increased the germination rate and growth of the plants. The lower dose of GO increased the plant growth, whereas higher doses showed adverse effects. Interestingly, GO increase the water uptake ability, oxygen content and efficiently translocate within the plants. Additionally, GO does not show any phytotoxic effect at a lower dose that makes promising materials for agriculture (He et al. 2018). Xie et al. use GO, and IAA-GO and tested against *Brassica napus* L. The data suggested that the GO inhibits the development of the roots. The co-treatment of phytohormones IAA-GO increased the inhibition rate. The exposure of GO increased the abundance of 1-aminocyclopropane-1-carboxylic acid synthase 2 (ACS2). The data suggested that the GO easily modulates various pathways to control the plants' growth (Xie et al. 2020). Park et al. synthesized GO using a chemical oxidation process and tested it against *Arabidopsis thaliana* L plants. The data suggested that the GO shows the constructive effects on the plants in terms of enhancing the length of roots, rate of flower bud formation, number of leaves, and area of leaves. Moreover, GO enhanced the size of fruits and ripening process, ultimately sweeter fruits than control plants fruits (Park et al. 2020). Mahmoud and Abdelhameed synthesized GO, lysine-GO (L-GO), and methionine-GO (M-GO) and tested against pearl millet (*Pennisetum glaucum* L.). The data suggested that the GO, L-GO, M-GO shows significant effect on the plants in terms of increasing the biomass accumulation, growth of the plants, photosynthetic pigments, and yield of the crops. Moreover, reducing reactive oxygen species (ROS) in plants under stress conditions (Mahmoud and Abdelhameed 2021). Figure 11.3 shows the photographic images of the pearl millet with exposure of GO, L-GO, and M-GO. Another study suggested focusing on the synthesis of GO and tested against different plants, mainly radish, alfalfa, lettuce, perennial ryegrass, and cucumber seeds. The data suggested that GO shows positive effects against radish, alfalfa, perennial ryegrass, and cucumber seeds. However, GO decrease the germination rate at lettuce plants. Moreover, phytotoxic effects were observed at a higher concentration of GO exposure. The data suggested that phytotoxicity depends on various factors like the amount of nanomaterials, plants species, and types of nanomaterials (Lee et al. 2021). Table 11.1 shows the comparative data of 2D-nanosheets, mainly graphene and GO, and its effects on different plants. The data suggested that the graphene and GO effectively increased the growth of the plants by increasing various factors like increased the root length, shoot length, biomass, chlorophyll content, protein content, photosynthesis process, water uptake ability, and germination rate. In general, 2D-nanosheets mainly graphene and GO has a potential ability that translocates within the plants. The higher translocation ability of the 2D-nanosheets improved growth and yield of the crops. Moreover,

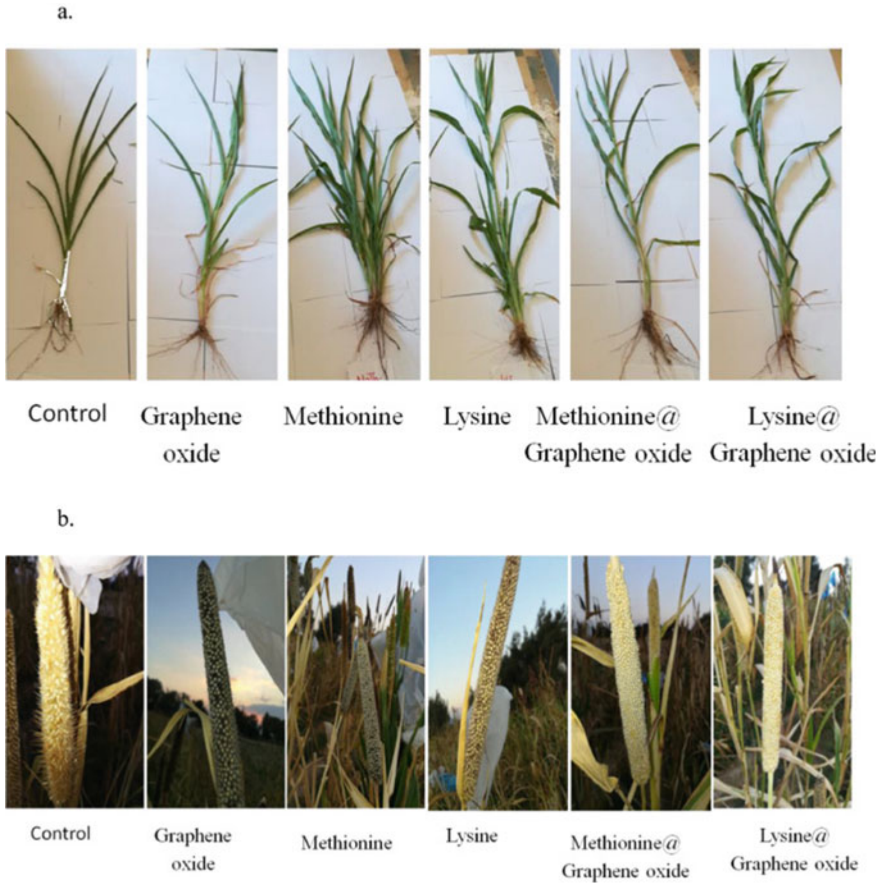

Fig. 11.3 Photographic images of the pearl millet with exposure of GO, L-GO, and M-GO. The figure was reproduced with permission (Mahmoud and Abdelhameed 2021)

the 2D-nanosheets do not show any toxicity at lower doses. However, high concentrations might show adverse effects in some plant species. The phytoxicity of the 2D-nanosheets mainly depends on various factors like types of nanomaterials, and types of plant species. Moreover, negatively charged graphene and GO effectively translocate within the plants.

Table 11.1 Different 2D-nanosheets and their effects on the plant growth

Nanosheets	Synthesis process	Plants	Effect of interaction	References
Graphene	Commercial	Tomato	Increased the germination rate	Zhang et al. (2015)
Graphene	–	Wheat	Induced oxidative stress, decreased chlorophyll content	Zhang et al. (2016)
GO	Commercial	Spinach	Increased the germination rate	He et al. (2018)
GO	Commercial	*Brassica napus* L	Inhibit the development of root	Xie et al. (2020)
GO	Chemical oxidation	*Arabidopsis thaliana* L	Increased the root length, fruit size, and sugar content	Park et al. (2020)
GO	Chemical oxidation	Pearl millet	It is increased plant growth, photosynthetic pigments, and biomass accumulation	Mahmoud and Abdelhameed (2021)
L-GO	Chemical oxidation	Pearl millet	It is increased plant growth, photosynthetic pigments, and biomass accumulation	Mahmoud and Abdelhameed (2021)
M-GO	Chemical oxidation	Pearl millet	It is increased plant growth, photosynthetic pigments, and biomass accumulation	Mahmoud and Abdelhameed (2021)
GO	Chemical oxidation	Lettuce, radish, alfalfa, perennial ryegrass, and cucumber seeds	Positive effects on plant growth. GO shows the negative impacts on lettuce	Lee et al. (2021)

11.5 2D-Nanosheets Based Hybrid Materials for Plant Growth and Protection

The 2D-nanosheets, mainly graphene and GO, are extensively used in agricultural applications. However, 2D-nanosheets shows toxic effect at higher doses that remains a concern. The researcher still focuses on modifying 2D-nanosheets for various aspects like incorporating the metal-nanoparticles and polymers that might improve the applicability and reduce the toxicity concern. Numerous 2D-nanosheets-based hybrid materials have been used for the improving growth and development of the plants (El Miri et al. 2016; Facure et al. 2017; Salim et al. 2021; Soraki et al. 2021; Rashidi Nodeh et al. 2017). For example, Zhang et al. synthesized fertilizers incorporated KNO_3 encapsulated graphene (F-K-Graphene) based hybrid materials and tested them for crop production. The data suggested that the F-K-Graphene-based hybrid materials release fertilizers in a controlled manner that might dramatically enhance the productivity of the crops (Zhang et al. 2014). Ren et al. synthesized sulfonated graphene and tested it against maize seedlings to determine oxidative stress at different concentrations. The data suggested that the sulfonated graphene increased the plant's growth at lower doses, whereas at higher doses decreased the development of the plants. Moreover, the rise in sulfonated graphene produces reactive oxygen species, reduces the soluble proteins, increases the enzymatic activity and intracellular Ca ions (Ren et al. 2016). Huang et al. synthesized C-14 labeled graphene (C-14-Graphene) and tested against rice plant. The data suggested that the C-14-Graphene increased the transformation and uptake within the plants that grew the plant growth and development (Huang et al. 2018). Soraki et al. synthesized Ag-nanoparticles and graphene-based hybrid materials and tested them against *Melissa officinalis.* The data suggested that the expression of synthase gene upon exposure to Ag-nanoparticles and Ag-graphene-based hybrid materials. Moreover, lower doses effectively induce the various molecular and biochemical pathways that enhance the growth of the plants (Soraki et al. 2021). Another study of the different group synthesized the similar Ag-graphene hybrid material and tested against *Stevia rebaudiana.* The data suggested that the Ag-graphene-based hybrid materials effectively increased the chlorophyll content, protein content, falvonoide content, accumulation of soluble sugar content, and total phenols. Moreover, the regulation of various molecular and biochemical pathways enhanced the growth and development of plants (Nokandeh et al. 2021). The above literature study suggested that the 2D-nanosheets-based hybrid materials effectively increased the growth of the plants and the yield of the crops. However, higher doses of the hybrid materials show the adverse effect that increased the production of reactive oxygen species. On the other hand, 2D-nanosheets-based hybrid materials also protect the crops against various pathogens. Several studies suggested that 2D-nanosheets-based hybrid materials effectively kill or protect the crops against pathogens. For example, Chan et al. synthesized Ag-graphene-based hybrid materials and tested them against *Fusarium graminearum.* The data suggested that the synthesized Ag-graphene-based hybrid materials efficiently inhibit the fungus in both *in-vitro* and *in-vivo*. The spore germination was inhibited even at a lower concentration of the hybrid materials. The mode of action of the hybrid materials might be increasing the production of reactive oxygen species and physical injury (Chen et al. 2016). Figure 11.4 shows the synthesis of Ag-graphene-based hybrid materials and their antifungal activity. Li et al. synthesized borneol-GO (B-GO) based hybrid materials and tested them against M. racemosus. The data suggested that the B-GO effectively inhibits the spore germination of the fungus. Moreover, no growth was observed up to five days of exposure, indicating the exceptional antifungal agents (Li et al. 2017). El-Abeid et al. synthesized Cu decorated reduced-GO (Cu-rGO) based hybrid materials and tested them against fusarium and wilt diseases of tomato and pepper plants. The data suggested that the Cu-rGO based hybrid materials effectively inhibit fungus growth and reduce wilt diseases without any phytotoxic effects up to 70 days (El-Abeid et al. 2020). Table 11.2 summarizes the comparative data of the different 2D-nanosheets-based hybrid materials and their impact on plant growth and crop protection. The study suggested that 2D-nanosheets-based hybrid materials effectively increased the growth and development of the plants by improving various molecular and biochemical pathways. Moreover, these 2D-nanosheets-based hybrid materials do not show any phytotoxic effects at lower doses, whereas some of the 2D-nanosheets-based hybrid materials show toxic effects at higher doses. The phytotoxicity of the 2D-nanosheets-based hybrid materials depends on various factors like types of 2D-nanosheets-based hybrid materials, plants, and species of the plants. 2D-nanosheets-based hybrid materials show lesser toxic effects compare with that of the 2D-nanosheets. Interestingly, the high translocation ability of the 2D-nanosheets-based hybrid materials aided advantageous that improved the delivery of micronutrients or fertilizers or agrochemicals, thereby high yield of the crops. Besides the growth and development of plants, 2D-nanosheets based hybrid materials are also effectively used for the protection of crops against various pathogens, as numerous polymers and metals have exceptional antimicrobial activity. In general, with the help of the 2D-nanosheets based hybrid materials we can easily improve plant growth as well as crop protection.

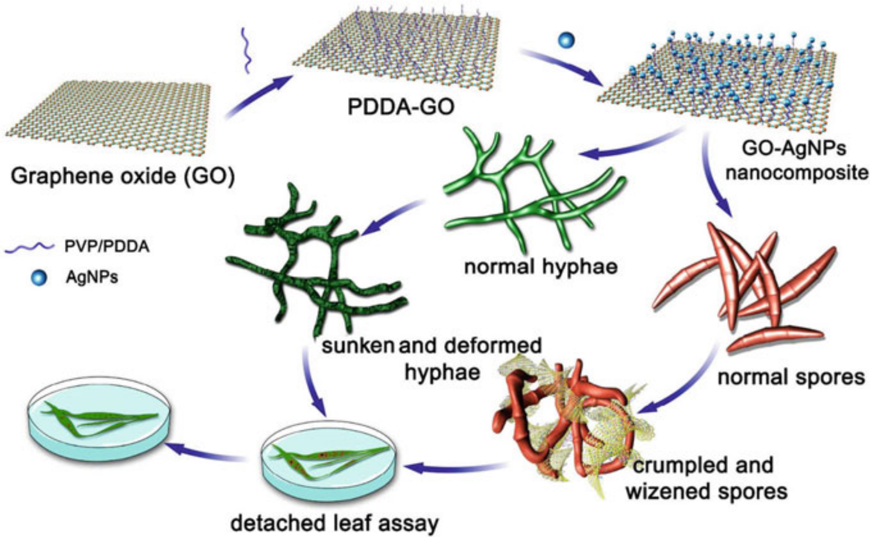

Fig. 11.4 Schematic representation of the synthesis of Ag-graphene-based hybrid materials and their antifungal activity. The image was reproduced with permission (Chen et al. 2016)

Table 11.2 Different 2D-nanosheets-based hybrid materials for plant growth and crop protection

Hybrid materials	Plants/Pathogens	Effects	References
Ag-graphene	*Melissa officinalis*	Low doses induce molecular and biochemical pathways	Soraki et al. (2021)
Ag-graphene	*Stevia rebaudiana*	Increased chlorophyll and protein content	Nokandeh et al. (2021)
Ag-graphene	*Fusarium graminearum*	Inhibit phytopathogens	Chen et al. (2016)
B-GO	*M. racemosus*	Inhibit fungal growth	Li et al. (2017)
Cu-rGO	Fusarium and wilt diseases	Inhibit spore germination	El-Abeid et al. (2020)
C-14-Graphene	*Rice*	Increased uptake and transformation	Huang et al. (2018)
F-K-GO	–	Controlled release of fertilizers	Zhang et al. (2014)
Sulfonated-graphene	*Maize*	Lower doses increased the plant growth, whereas higher concentration decreased	Ren et al. (2016)

11.6 Conclusion and Prospects

Tis chapter has addressed the synthesis of 2D-nanosheets or NMs, the interaction of 2D-nanosheets with plants, the role of 2D-nanosheets in the growth and development of plants. The effect of 2D-nanosheets-based hybrid materials for plant growth and crops protection was also discussed. The nano-sized and negatively charged 2D-nanosheets might be beneficial for effective translocation ability. Additionally, with the help of a functional group, tuning the surface charge of the 2D-nanosheets can be easily achieved. The higher translocation ability of the NMs or 2D-nanosheets efficiently enhanced the plant growth, development, and yield of the crops by increasing protein content, chlorophyll content, root-shoot length, germination rate and water uptake ability. 2D-nanosheets-based hybrid materials are also effectively used for the protection of crops against various pathogens. Therefore, the 2D-nanosheets-based hybrid materials can potentially improve plant growth and crop protection that might be next-generation tools for agriculture. Polymeric delivery system might be beneficial for the real-time application of NMs.

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