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REVIEW PAPER

Influence of nano-priming on seed germination and plant growth of forage and medicinal plants

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Abstract
Plant growth and development are vastly affected by different abiotic and biotic stresses. Seed priming is an effective tool for increasing seed germination and plant growth that will eventually increase productivity under different environmental conditions and stresses. Efficient seed germination promotes successful establishment and deep root system of plants. Among the different seed priming methods, nano-priming is more effective mainly because of its small size and unique physicochemical properties. Since plant species are physiologically different, they differ in their uptake of nanoparticles in nano-priming, and hence in their rate and manner of growth. Most previous studies have separately investigated the effect of nanomaterial on seed germination, growth, and development of one plant at a time. However, very few studies have reported nano-priming effects using different particles on seed germination and seedling growth of forage and medicinal plants together. Therefore, this review summarizes studies of nano-priming effects using various particles on seed germination and seedling growth of forage and medicinal plants. Furthermore, the effect of different nanoparticles on the most important characteristics of germination, morphology and physiology affecting the establishment, growth and production of these plants are reviewed. In general, nano-priming increased seed germination, seedling growth and development, vigor, rate of seedling emergence and subsequent performance in most of the medicinal and forage plants. While the use of nanoparticles enhanced environmental stress resistance of these plants, negative effects of nano-priming on seed germination, seedling and plant growth traits were observed. In addition, future research areas of focus are discussed briefly.

Keywords Seed priming · Nanoparticles · Seed germination · Plant growth · Forage · Medicinal plants

Introduction

Plant life begins with seed germination, and successful germination plays a key role in the survival and conservation of plant species, particularly in agricultural and rangeland ecosystems (Manjaiah et al. 2019). Moreover, the germination stage is one of the most sensitive phases related to drought and salinity stresses, and if a plant can withstand these stresses, it can also pass subsequent stages of growth (Soltani and Soltani 2015). The growth and productivity of plants depend on the speed and homogeneity of the seedlings that will shield buds from damages due to undesirable environmental conditions. Seed germination, and then seedling development are strongly affected by environmental factors, particularly, temperature, moisture, drought, and salinity (Zahedifar 2013). Efficient seed germination is important for increasing the production of forage and medicinal plants in rangeland and agricultural fields. Rapid and homogeneous seedling emergence eventually leads to successful establishment and deep root system of plants (Azimi et al. 2014). Forage production is declining in different parts of the world due to problems of germination, overgrazing, drought, and environmental stresses. On the other hand, a special attention is being paid to the use of medicinal plants, primarily due to its lower side effects compared to that of chemical medicines. The medicinal importance of some plants is mainly due to the presence of active ingredients such as terpenes, flavonoids, coumarins, carotenoids, essential

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oils, and amino acids (Ahmad et al. 2018). But, in many ecosystems, seed germination and seedling growth of these plants are reduced due to various stresses. Therefore, it is essential to use appropriate methods to increase germination, seedling growth, and development (Soltani and Soltani 2015).

Seed priming is one of the outstanding methods that result in quick and monotonous germination, seed quality and seedling establishment that leads to enhanced plant growth (Ibrahim 2016; Abid et al. 2018; Thejeshwini et al. 2019). Seed priming can improve the germination of weak, damaged, or aged seeds, even during adverse environmental conditions (Dragicevic et al. 2013). Seed priming has been recognized as a potential method of improving plant yield by increasing plant tolerance to abiotic and biotic stresses. There are several other benefits of seed priming, including synchronized and rapid germination, improved water use efficiency, better nutrient uptake, higher range of germination temperature, and improved concurrent maturity of plants (Hill et al. 2008; Dutta 2018). One of the major challenges of today's plant production system is ability to produce food products that meet the needs of the growing global population in an environmentally sustainable way. Therefore, seed priming can be the best and most suitable solution for further germination, establishment, and yield of plant products, especially in adverse conditions (Singh et al. 2015).

Nanotechnology affects almost all existing scientific fields, and the entry of nanoparticles (NPs) into the agricultural world has a great potential for addressing agricultural sustainability issues (Fraceto et al. 2016; Maghsoodi et al. 2019). Different studies showed that the application of NPs has positive effects on seed germination as well as on plant growth and development. This is because using nanoparticles, as a seed priming technique, is effective due to its small size and unique physicochemical properties (Dasgupta et al. 2017). NPs are molecular or atomic aggregates with at least one dimension between 1 and 100 nm, which can substantially improve their chemical and physical properties in comparison to the bulk materials (Sharon et al. 2010; Khadem Moghadam et al. 2019). Nano-priming (priming using nanomaterials of micronutrients) increases the seed germination, seedling growth and development and vigor as well as seedling dry weight in most of the plants (Ghafari and Razmjoo 2013). Furthermore, since nano-priming triggers special metabolic processes that are naturally activated during the early phase of germination, it increases seed germination, rate of seedling emergence, growth, production, and quality of the crops (Acharya et al. 2020). It also modulates how plants interact with their environment at both cellular and molecular levels (Li et al. 2019). The goal of using NPs in agriculture and natural ecosystems is to increase the performance and sustainability of plants and soil by using less inputs (Abbasi Khalaki et al. 2019b).

Although the adoption of recent improvements in the use of nanotechnology in agriculture and natural ecosystems is increasing, there is no comprehensive study on the positive and the negative effects of nanoparticles as nano-priming on germination, establishment and growth of medicinal and forage plants together. On the other hand, most previous studies have separately investigated the effect of one nanomaterial on seed germination, growth and development of only one plant (most of them were on a crop). Therefore, the focus of this review is on studies of nano-priming effects using different particles on seed germination and seedling growth of forage and medicinal plants. Furthermore, the effects of different nanoparticles on some of the most important characteristics of germination, morphology and physiology affecting the establishment, growth and production of these plants are also reviewed. This is because these factors are economically and practically important. In general, this study summarizes: (i) a brief introduction of seed priming and nano-priming, (ii) high usage of nanoparticles in seed priming, (iii) the positive effects of different nanoparticles on seed germination and seedling traits of forage and medicinal plants, (iv) the positive effects of nano-priming on growth and establishment of these plants in field, and (v) the negative effects of nano-priming on seed germination, seedling and growth traits of forage and medicinal plants.

Priming technology and nanotechnology in plants

Seed priming is a pre-sowing treatment that puts seeds in a specific concentration of defined solution for a specified period. Priming creates a physiological state in the seed that strengthens its growth capacity against biotic or abiotic stresses (Conrath 2011). Priming can accelerate germination rate, speed of germination, vigor index of seedling, root and shoot elongation, wet and dry weight of seedling, photosynthetic rate, and other growth traits of plants (Siddique and Bose 2007).

The purpose of seed priming is to treat seeds with diverse agents, such as water, that activate physiological processes of seeds. If time vs. seed water content is plotted, then primed seeds and non-primed seeds demonstrate three phases. The first phase (Phase I: Imbibition) represents the entry of water in the seed by the process of adsorption. The second phase (Phase II: Activation) is initiation of biochemical processes and demonstrates hydration in non-primed seeds. In primed seeds, hydration treatment permits controlled imbibition and induction of the pre-germinative metabolism, but radicle emergence is prohibited. The third phase (Phase III: Growth) displays the germination and post-germination phase which causes sugar consumption by the embryo and radicle growth and is similar in non-primed and primed seeds (Nascimento and Aragao 2004; Rajjou et al. 2012) (Fig. 1). Moreover, priming actuates metabolism before germination that contains a vast scope of physiological operations such as repair pathways of DNA and reactive oxygen species (Paparella et al. 2015). Therefore, seed priming is a low-cost, simple, and suitable technique for enhancing germination and seedling establishment, and eventually increasing plant yield, particularly under stress conditions (Singh et al. 2015).

There are different priming methods: hydropriming (seed soaking in water) (Finch-Savage et al. 2004), osmopriming (soaking in osmotic solutions) (Abbasi Khalaki et al. 2018), halopriming (soaking in inorganic salt solutions) (Bekhrad et al. 2015), hormo-priming (putting in the solution of growth regulators) (Abbasi Khalaki et al. 2018), matrix priming (putting at low and high temperatures), bio-priming (soaking in an organic matter solution) (Moameri et al. 2018a), and nano-priming (seed soaking in nanomaterials) (Moameri et al. 2018a; Abbasi Khalaki et al. 2019a).

The success of priming depends on a combination of interacting factors such as plant, water, priming treatment, priming period, temperature, vigorness of the seed, and seed storage conditions. Several studies have showed that NPs have an ability to infiltrate in the coat of seeds and increase water uptake, which augments germination and growth (Maroufpoor et al. 2019).

The *nano* prefix was derived from *Nanos,* a Greek word, meaning *dwarf*, and became prominent in the scientific literature. Nanotechnology has become an interdisciplinary field of research in most of the new sciences, and many nano words such as nanoscale, nanotechnology, nanostructures, nanotubes are found in dictionaries (Buzea et al. 2007). Nanotechnology has a very considerable impact on industry, economy, and human's life all over the world. Green nanotechnology is a new field of research involving the design of nanomaterials, nanoscale and processes through green chemistry and engineering leading to the development of new functions without harmful subsequences on biosphere and humanity (McKenzie and Hutchison 2004).

NPs are numerous in nature and are created in many natural operations such as volcanic eruptions, photochemical reactions, forest fires, erosion, and shedding of plants and animal hair (Buzea et al. 2007). Most organisms, especially those that interact strongly with their surroundings, are affected by exposure to NPs. Priming with micronutrients has been recognized as a possible technique for enhancing germination rate, and the development of seedling vigor. The type and the magnitude of the effect of NPs on plant germination depend on the plant species, the concentration of NPs in the environment, the contact time, the intrinsic properties of nanomaterials, and the interaction between living environment and plant (Ma et al. 2010; Miralles et al. 2012).

The use of nanotechnology to optimize the formulation of chemical fertilizers can attain remarkable achievements, including reducing energy consumption and production costs, and minimizing environmental damages. NPs can reach plant or soil systems through two paths: agricultural and industrial sewages that often have nanomaterials such as TiO_2, SiO_2, Ag and ZnO NPs (Gottschalk et al. 2009; Pradas del Real et al. 2016); and through the use of nano-agrochemicals including nano-fertilizers, nano-amendments and nano-pesticides that contain TiO_2, SiO_2, Cu/CuO/Cu $(OH)_2$, Fe/FeOx, Zn/ZnO, Ag, Au and CeO_2 NPs (Kah et al. 2018). Then, NPs are first absorbed through the plant's root and shoot, and then move to the tissues (Dietz and Herth 2011).

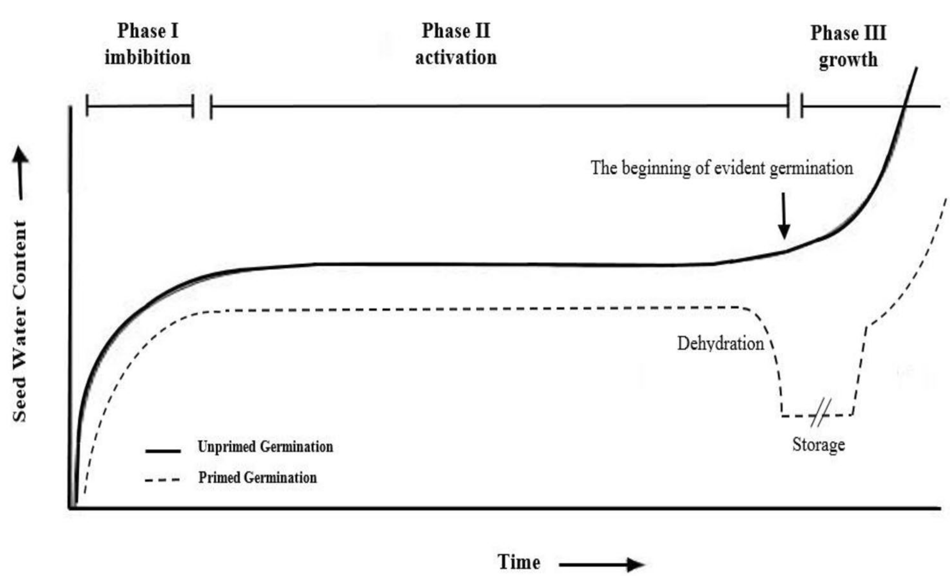

Fig. 1 Schematic diagram of three-step pattern of water uptake by germinating seeds and seed priming process

High usage of nanoparticles in seed priming of forage and medicinal plants

Nanotechnology has been noticed as a reputable and novel field during the last few decades. Nanotechnology discoveries have opened new application opportunities in different areas of biotechnology, agriculture, and natural resources such as food chain, rangelands restoration and environmental sustainability (Nair et al. 2010). Although fertilizers are vital for better growth of plants, most of their compounds are not available to all plants because of leaching, rottenness by photolysis, hydrolysis, and parsing. Hence, there is a need for reducing fertilizer nutrient losses, and using nanotechnology and NPs based novel techniques to improve the productivity of plants (Nair et al. 2010; DeRosa et al. 2010). Different NPs (metal and metal oxide NPs) can decrease or increase the germination of many plant seeds (Feizi et al. 2013). However, Ag, Au, CuO, ZnO, CeO_2 and TiO_2 are the most prevalent metal oxide and metal NPs studied by most plant science researchers (Maroufpoor et al. 2019). Some of these materials are reviewed below, and their scanning electron microscope (SEM) pictures are shown in Fig. 2.

Silver nanoparticles (AgNPs)

Currently, AgNPs are among the most commonly used nanomaterials; and are among the most widely used nanoparticles after carbon nanotubes. These NPs are extensively used for their antimicrobial attributes in many sciences such as textiles, plastics, and detergents (Awasthi et al. 2017).

AgNPs are also cherished due to their unique attributes (e.g., desired magnetic, optical and electrical characteristics), which can be combined into electronic materials, composite fibers, antimicrobial applications, cryogenic superconducting components, cosmetic products, biosensor materials and prevention of ethylene act in plants. The ability of AgNPs to protect seeds from bacteria and fungi makes them potentially useful in gardening and other agricultural activities (Parveen and Rao 2015).

Silica nanoparticles (Si NPs)

Silicon (Si) is recognized as the second common element, after oxygen, accounting for approximately 31% of Earth's crust (Dietz and Herth 2011). Some researchers stated that Si could improve salt stress distress on plants (Wang et al. 2011). Si has a role in improving the mechanical strength of leaves, light absorption, plant growth, enhancing photosynthesis capacity, endurance of plant organs, reducing evapotranspiration, and improving plant tolerance against abiotic and biotic stresses. Si exists in the epidermis tissue of a plant secretory organs (Maghsoudi et al. 2019). Nanosilica is an important material that can be used in different fields of technology and science including electronics, and biomedical applications.

Many field studies under different climate and soil conditions, and with various plants have shown that application of silicon fertilizers enhance crop quantity and quality. Silicon NPs have distinct physiological properties that allow them to affect metabolic activities of plants (Rastogi et al. 2019). In addition, silica NPs can deliver chemicals and DNA into plants as well as in animal tissues (Torney et al. 2007). Nano-silica enhances germination attributes including germination rate, radicle height, and plant dry weight (Azimi et al. 2014).

Copper nanoparticles (Cu NPs)

Copper (Cu) is an essential element for plant growth and photosynthetic reactions. It is involved in the process of photosynthesis and exchange of hydrocarbons and proteins. Copper is also part of several oxidizing enzymes, such as ascorbic acid oxidase and polyphenol oxidase (Leng et al. 2015). Cu is necessary for plant growth and metabolism, and its deficit in plants is revealed by curled leaves; however, higher than the optimum concentration can result in toxicity effects (Passam et al. 2007). Discharge of Cu NPs from various products may have toxic effects on the health of humans and ecosystems (Chen et al. 2012). Previous studies have revealed that copper oxide (CuO) NPs had toxic effects on aquatic organisms such as algae, crustaceans, zebra fish and protozoa (Nair and Chung 2014). However, lower concentration of CuO NPs was reported to be desirable for seedling growth, germination, and metabolism of *Vigna radiata* (L.) R. Wilczek (Singh et al. 2017). But, since the influence of Cu NPs on plants has not been investigated thoroughly, previously reported results are not clear (Lee et al. 2008).

Iron nanoparticles (Fe NPs)

Iron (Fe) ranks fourth among earth's crustal metals and has been characterized as a non-toxic metal (Li et al. 2006). Iron is a vital micronutrient for all organisms. In plants, it has an important role in chlorophyll biosynthesis, photosynthesis, and respiration (Najafi Disfani et al. 2016). Fe NPs are among the diverse nanoparticles used for environmental (Peeters et al. 2016) and wastewater (Fu et al. 2014) remediation. Iron oxide (FeO) NPs have an important role in germination, efficient growth of plants, and yield increase. Increasing FeO NPs reduces

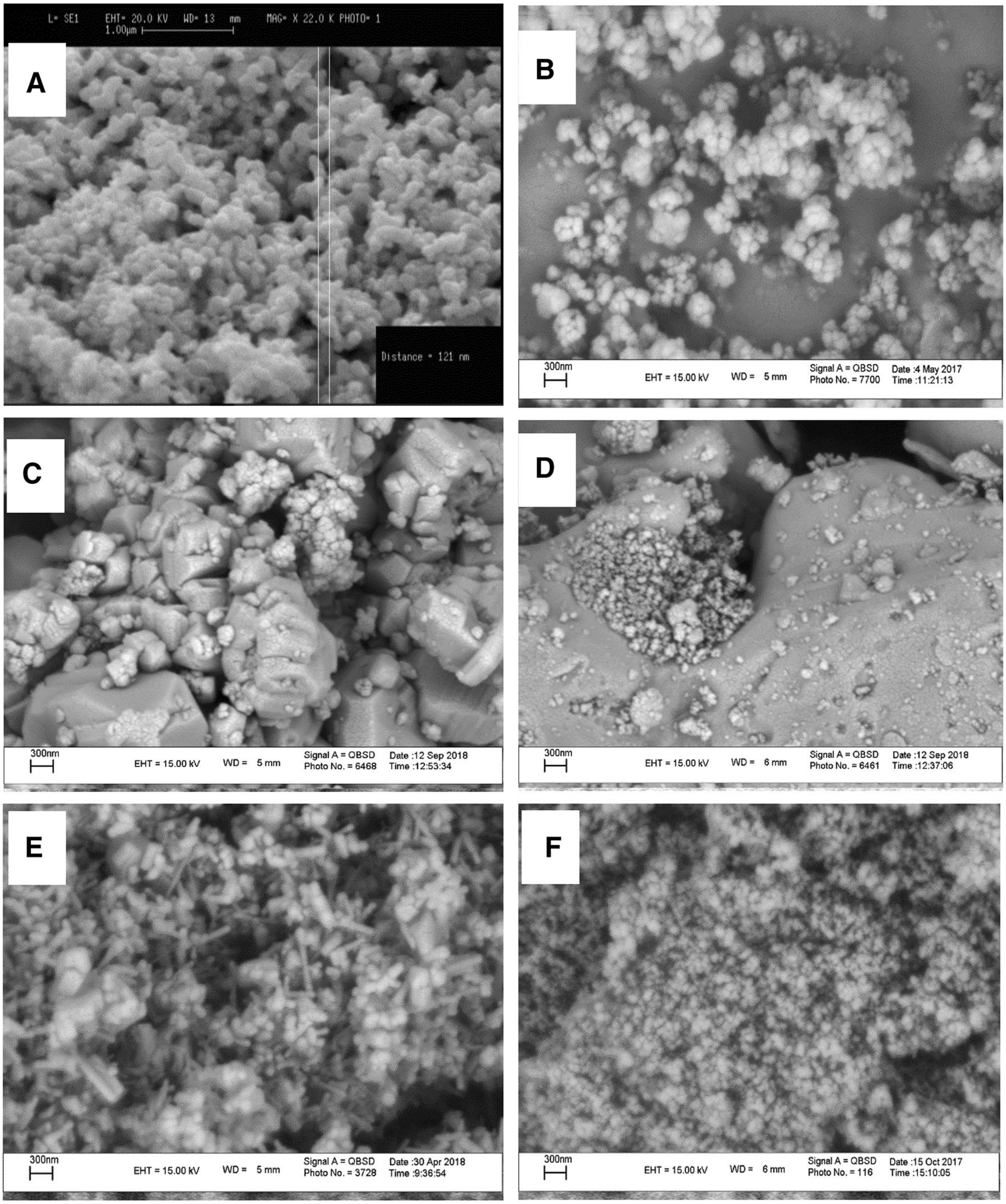

Fig. 2 Scanning electron microscope (SEM) micrograph of investigated nanoparticles. **a** Ag, **b** Si, **c** Cu, **d** Fe, **e** Zn, **f** Ti

iron deficiency and increases chlorophyll a as well as chlorophyll b because iron is the major element of the chlorophyll molecule (Mohammad et al. 2013). Thus, iron oxide nanoparticles, through their essential properties for plants have an important effect in the development of agriculture and other sciences (Naseri et al. 2015). FeO NPs are also applied as nano-fertilizers to enhance accessibility of iron to plants, to control the antioxidant enzymes and phytohormones' function, and to boost plant biomass, height, and root length (Rui et al. 2016; Shankramma et al. 2016).

Zinc oxide nanoparticles (ZnO NPs)

Zinc is an essential ingredient for plant growth due to its role in chlorophyll synthesis and carbohydrate formation. Improving zinc level in plants decreases the uptake of noxious heavy metals and reduces its toxic effects on plants. Zinc oxide nanoparticles are used in different fields such as industry, medicine, domestic products, biosensors, and electrodes. However, Zn NPs are mainly used in agriculture (Awasthi et al. 2017; Agarwal et al. 2017), and they play a pivotal role in anatomical and physiological responses of plants (Agarwal et al. 2017). ZnO plays a key role in regulating the metabolism of plant hormones, and it is necessary for several enzyme activities, such as dehydrogenases and superoxide dismutase (Narendhran et al. 2016). Zinc oxide nanoparticles can be used as chemical absorbents, antibacterial, catalysts and polymer additives because of their low toxicity, long life-span, large specific surface area, high pore volume, and photodegradation. There are some recent studies that focused on the influence of ZnO NPs on seed germination of various plant species (Burman et al. 2013; Marslin et al. 2017). On the other hand, it was reported that the usage of ZnO-NPs nano-fertilizer can have toxic effects on plants through metal-based NPs biological activity (Xiang et al. 2015). Some researches declare that nano-ZnO is one of the most toxic nanoparticles that could terminate root growth of plants (Wang et al. 2013).

Titanium nanoparticles (nano-Ti, nano-TiO_2)

Nano titanium dioxide (nano-TiO_2) has high photocatalytic activity and is used as a catalyst in water, electronic devices, energy conversion equipment, and energy storage (Kenanakis and Katsarakis 2014; Asgari Lajayer et al. 2018). Nano-TiO_2 controls the activity of nitrogen metabolism enzymes such as glutamine synthase, nitrate reductase, and glutamate dehydrogenase that help plants to absorb nitrate and convert the inorganic nitrogen to organic nitrogen, that will eventually increase the dry and fresh weight of plants (Mishra et al. 2014). TiO_2 NPs help to increase seed water absorption, boost vigor of old seeds, prevent aging of chloroplasts, increase formation of chlorophyll, improve light absorbance, enhance photosynthesis, and subsequently to increase plant growth and establishment (Qi et al. 2013). On the other hand, some studies reported both positive and negative effects of TiO_2 nanoparticles on plants (Castiglione et al. 2011).

Gold nanoparticles (Au NPs)

Au NPs are metallic nanoparticles that were studied and used since the 16th century for painting and medical goals (Kumar et al. 2013). Gold NPs are recognized as the most stable metal NPs. The different applications of gold NPs include therapy, catalysis, immune-sensing, disease diagnostics, cancer cell diagnostics and treatment, medicine, agriculture, and plant science (Mayer et al. 2008; Savithramma et al. 2012; Kumar et al. 2013). Also, the presence of gold nanoparticles, with diameter of 0.5 to 100 nm, has been confirmed in many plant tissues (Judy et al. 2012).

Positive effects of nano-priming on seed germination and seedling traits of forage and medicinal plants

Plants, as essential components in all ecosystems, play an important role in the transportation of NPs into the environment. These particles can have a positive or a negative impact on plants (Ma et al. 2010). One of the critical stages in the life cycle of plants (such as forage and medicinal plants) is germination and early seedlings growth (Nee et al. 2017). Priming could improve the germination of seeds under stress conditions compared to unprimed seeds (Sharifi and Khavazi 2011).

Rapid and uniform germination of seeds leads to successful establishment of plants. Therefore, the study of germination and growth of primed seeds is important. In seed priming studies, several germination and seedling growth indices are examined to determine the positive or the negative effects of the material used. The most important indicators measured in different studies are shown in Table 1.

Different plant species are different in their physiology, and these differences lead to differences in their NPs uptake into nano-priming and the variations in the rate and manner of species growth (Zhu et al. 2012). Studies on the use of different nanoparticles in germination and early seed growth of some forage and medicinal plants are presented in Table 2.

Positive effects of nano-priming on the growth and establishment of forage and medicinal plants

Due to lack of moisture, plant growth and establishment in the arid and semi-arid rangelands is a serious problem, especially at the beginning of the growing season. The establishment of plants is essential for the efficient use of resources such as water and light. Thus, uniform and proper establishment of plants is a pre-requisite for their success. Delayed emergence and inappropriate establishment can reduce the future growth rate of the plants. Seed priming is one of the simple techniques for increasing seedlings' emergence rate, recovery power, and seedling establishment that will eventually improve the growth efficiency of the plant in the field (Abbasi Khalaki et al.

Table 1 The method of calculating seed germination and seedling traits

Studied Indices	Formula	Unit	References
Germination Percentage (GP)	$GP = \frac{N_i}{N} \times 100$	%	Khan and Ungar (1998)
Speed of Germination (SG)	$S = \frac{n_i}{d_i}$	Number/day	Khan and Ungar (1998)
Mean Germination Time (MGT)	$MGT = \frac{\sum n_i \times d_i}{N}$	Day	Ellis and Roberts (1982)
Root Length (RL)	Ruler	Cm	Lee et al. (1998)
Shoot Length (SL)	Ruler	Cm	Lee et al. (1998)
Wet Weight (WW)	Precision scale	G	Seibert and Pearce (1993)
Dry Weight (DW)	Precision scale	G	Seibert and Pearce (1993)
Vigor index (Vi)	$Vi = (RL + SL) \times GP$	Cm %	Abdul–Baki and Anderson (1973)
Allometric Coefficient (AC)	$AC = \frac{SL}{RL}$	–	Scott et al. (1984)

N total number of seeds; N_i number of germinated seeds at the end of counting days; n_i number of germinated seeds per day; and d_i number of counting days

2019a). Besides boosting the growth and the yield of plants, NPs have an important role in plant conservation against various abiotic stresses by minimizing anti oxidative enzymatic activities (Rico et al. 2013).

Plants can produce natural mineralized NPs needed for their growth under certain conditions. Meanwhile, nanofertilizers have beneficial attributes for enhancing crop yield and production (Nair et al. 2010; DeRosa et al. 2010), and for reducing nutrient fatality in fertilization and environmental hazard (Conley et al. 2009). For example, SiO_2 NPs increases photosynthetic rate, which is a vital process for plant growth and sustainability, by improving the synthesis of photosynthetic pigments (Siddiqui et al. 2014). Silver compounds, including silver salts, water-soluble silicates and polymers, and their radioactive rays are also excellent stimulants of plant growth (Sharon et al. 2010). Nanomaterials are used to regulate the growth of ornamental plants and plants used in biofuels, as well as plants specifically produced for the extraction of metabolites and proteins. However, few studies have been conducted on the effects of nanoparticles on biosynthesis in different types of secondary metabolites in medicinal plants. In a study on the effect of titanium dioxide nanoparticles on quantitative traits, essential oil, and concentrations of thymol and carvacrol of *Thymus vulgaris* under different levels of water stress, it was reported that essential oil was affected negatively by water stress, but not by titanium dioxide nanoparticles (Fazeli-Nasab et al. 2018). This could be because nanoparticles have unique physical and chemical properties that would enhance the metabolism of plants (Giraldo et al. 2014). As shown in Fig. 3, there are various pathways for NPs synthesis by plant system.

Commonly used traits of plants in different studies include plant height, basal diameter, canopy cover, total biomass, number of florescence, viability, 1000-grain weight, total chlorophyll, photosynthesis rate, and leaf area index (Moameri et al. 2018b). The relative water content (RWC) of leaf is calculated using the following formula (Koochaki and Sarmadnia 2012).

$$RWC = \left(\frac{FW - DW}{SW - DW}\right) \times 100$$

where FW = fresh leaf weight immediately after sampling, DW = dry weight of leaf after drying in oven, and SW = saturated leaf weight after placing in distilled water.

Currently, with proper management and application of modern techniques, available rainfall and water resources can be used to conserve and store water in the soil. These include the use of nanotechnology and changes in soil properties using various amenders. Application of these materials in soil can increase soil moisture retention capacity, reduce irrigation and fertilizer costs, biologically regenerate and succeed in irrigation and seedling programs, and reduce the effects of environmental stresses (Liu and Lal 2015). Hence, the use of NPs in plant growth has been an important and efficient practice. Some examples of the use of different nanoparticles in the growth and development of a number of forage and medicinal plants are shown in Table 3.

Negative effects of nano-priming on seed germination, seedling traits and plant growth of forage and medicinal plants

Despite their benefits, nanomaterials may have toxicity impacts on the safety and biodiversity of aquatic and terrestrial systems. Also, toxic influences of NPs have been reported on microorganisms and animals (Menard et al. 2011). The toxic effects of NPs on plants include deterrence of seed emergence, reduction of seedling numbers, prohibition of stem and root growth, and postponement of flowering and reduction of yield (El-Temsah and Joner 2010; Li et al. 2015). The chemical and physical properties of NPs associated with toxicity to bio systems include element composition, porosity, average size, surface area, surface charge, aggregation propensity, and hydrodynamic diameter (Paralta-Videa et al. 2011). The agglomeration and

Table 2 The positive effects of nanoparticles on seed germination and seedling traits

Nano-particle	Result (Positive effects)	Plant species	Usage		References
			Forage	Medicine	
Au	Seed germination; seedling growth	*Boswellia ovalifoliolata*		✓	Savithramma et al. (2012)
	Seed germination; seed yield; vegetative growth	*Arabidopsis thaliana*		✓	Kumar et al. (2013)
Si–SiO_2	Germination percentage; root and shoot length; wet and dry weight	*Agropyron elongatum*	✓		Azimi et al. (2014)
	Allometric coefficient; shoot length	*Onobrychis sativa*	✓		Moameri et al. (2018a)
	Seed germination	*Astragalus squarrosus*	✓		Azimi et al. (2016)
Ag	Germination percentage; root and shoot length; wet and dry weight; average germination time; vigor index	*Thymus kotschyanus*		✓	Abbasi Khalaki et al. (2016)
	Germination percentage; speed of germination	*Boswellia ovaliofoliolata*		✓	Savithramma et al. (2012)
	Germination percentage	*Eupatorium fistulosum*		✓	Yin et al. (2012)
	Seed germination	*Pennisetum glaucum*	✓		Parveen and Rao (2015)
	Seed germination	*Bacopa monnieri*		✓	Krishnaraj et al. (2012)
	Seed germination; root and shoot length	*Thymus vulgaris*	✓		Ghavam (2019)
	Germination percentage; speed of germination; vigor index; mean germination time; allometric coefficient	*Festuca ovina*	✓		Abbasi Khalaki et al. (2019a)
	Seed germination; seedling growth	*Boswellia ovalifoliolata*		✓	Savithramma et al. (2012)
	Seed germination; root and shoot length	*Thymus vulgaris*	✓		Ghavam (2019)
	Germination percentage; speed of germination; vigor index; average germination time; allometric coefficient	*Festuca ovina*	✓		Abbasi Khalaki et al. (2019a)
Au	Seed germination; seedling growth	*Boswellia ovalifoliolata*		✓	Savithramma et al. (2012)
	Seed germination; seed yield; vegetative growth	*Arabidopsis thaliana*		✓	Kumar et al. (2013)
Si–SiO_2	Germination percentage; root and shoot length; wet and dry weight	*Agropyron elongatum*	✓		Azimi et al. (2014)
	Allometric coefficient; shoot length	*Onobrychis sativa*	✓		Moameri et al. (2018a)
	Germination rate; root and shoot length; wet and dry weight; vigor index	*Thymus kotschyanus*		✓	Abbasi Khalaki et al. (2016)
	Seed germination	*Astragalus squarrosus*	✓		Azimi et al. (2016)
Fe–FeO–Fe_2O_3	Mean germination time	*Hordeum vulgare*	✓		Najafi Disfani et al. (2016)
	Mean germination time	*Zea mays*	✓		Najafi Disfani et al. (2016)
	Seed germination	*Lolium perenne*	✓		Wang et al. (2011)
Ti–TiO_2	Germination percentage; speed of germination	*Onobrychis sativa*	✓		Moameri et al. (2018a)
	Seed germination; vigor index; germination percentage; speed of germination	*Petroselinum crispum*		✓	Dehkourdi and Mosavi (2013)
	Germination rate; mean germination time; shoot dry weight; vigor index	*Foeniculum vulgare*		✓	Feizi et al. (2013)

permanence effect of NPs on plant growth and metabolism depend on the chemistry, concentration, and size of NPs (Dietz and Herth 2011). Smaller NPs have more toxic effects on the cell because of their higher surface energy.

Currently, research on the toxicity of nanoparticles has increased due to their widespread use. Absorbance and toxicity of NPs to animals, humans and, in some cases, to plants have been researched in diverse experiments (Dietz and Herth 2011).

Different levels of toxicity have been reported for various types of nanoparticles, such as carbon nanotubes, fullerene, metals, and metal oxides (Klaine et al. 2008; Pachapur et al. 2016). There are environmental hazards related to the use of metal and metal oxides NPs in different fields (Palimi et al. 2015). The deterrence of NPs might be attributed to two main factors: (1) the dependence of chemical toxicity on the release of toxic ions, such as penetration and dissolution of NPs, and (2) stress

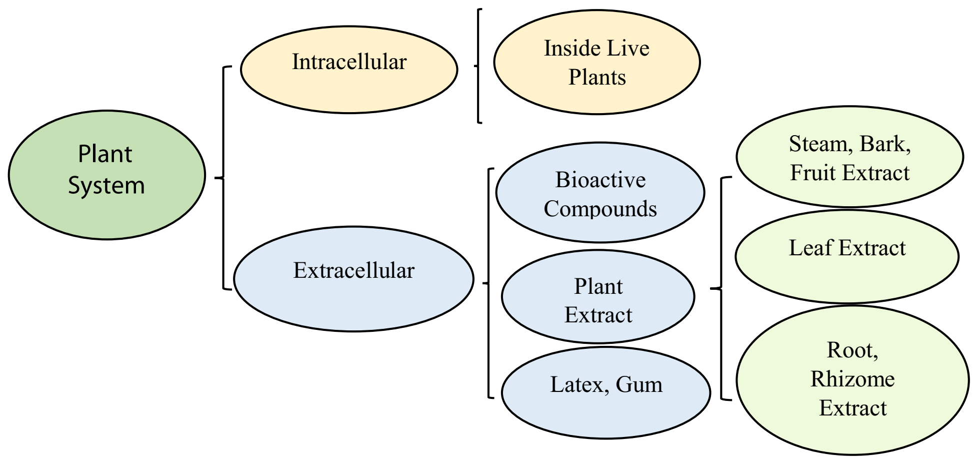

Fig. 3 Various pathways of metal nanoparticles synthesis by plant system

Table 3 The positive effects of nanoparticles on rangeland plants growth and establishment

Nano-Particle	Result (Positive effects)	Plant species	Usage		References
			Forage	Medicine	
Ag	Root length; shoot length; leaf area; chlorophyll	*Brassica juncea*		✓	Sharma et al. (2012)
	Root length; shoot length; chlorophyll content	*Sorghum bicolor*	✓		Namasivayam and Chitrakala (2011)
	Root length; wet and dry weight of root	*Crocus sativus*		✓	Rezvani and Sorooshzadeh (2014)
Si–SiO_2	Plant height; basal area; canopy cover; sub branch; depth of rooting	*Thymus Kotschyanus*	✓		Abbasi Khalaki et al. (2019b)
	Basal area; canopy cover; number of florescence; root area; viability	*Alopecurus textilis*	✓		Abbasi Khalaki (2019)
	Plant height and tillers; plant yield; wet and dry root mass	*Medicago sativa*	✓	✓	Zmeeva et al. (2017)
	Plant transpiration; chlorophyll and carotenoids; photosynthetic pigments	*Medicago sativa*	✓	✓	Ma and Yamaji (2006)
	Leaf fresh and dry weight; chlorophyll content	*Ocimum basilicum*		✓	Siddiqui et al. (2007)
Zn–ZnO	Plant growth	*Capsicum annuum*		✓	García-López et al. (2018)
	Plant biomass; shoot and root length; root area; chlorophyll content	*Cyamopsis tetragonoloba*		✓	Raliya and Tarafdar (2013)
	Root elongation; biomass	*Hordeum vulgare*	✓		Najafi Disfani et al. (2016)
Fe–FeO	Shoot length; root elongation; biomass	*Zea mays*	✓		Najafi Disfani et al. (2016)
	Root elongation; biomass	*Hordeum vulgare*	✓		Najafi Disfani et al. (2016)
	Shoot and root growth	*Lolium perenne*	✓		Wang et al. (2011)
Fe–FeO	Chlorophyll content	*Satureja hortensis*		✓	Peyvandi et al. (2011a)
	Photosynthesis rate; chlorophyll content; wet and dry weight of plant; shoot and root length	*Ocimum Basilicum*		✓	Peyvandi et al. (2011b)
	Plant growth	*Capsicum annuum*		✓	Yuan et al. (2018)
Cu–CuO	Shoot and root length; fresh weight; chlorophyll content	*Petroselinum crispum*		✓	Dehkourdi and Mosavi (2013)
NanoSe	Growth of root system	*Nicotinia tabacum*		✓	Domokos-Szabolcsy et al. (2012)
Ti–TiO_2	Essential oil content and yield; active ingredient content	*Mentha piperita*		✓	Ahmad et al. (2018)
	The amount of essence, thymol and carvacrol	*Thymus vulgaris*		✓	Fazeli-Nasab et al. (2018)

or exciter related to shape, size or surface of the NPs (Lee et al. 2010). In a study on the effect of copper nanoparticles on mung bean and wheat, Lee et al. (2008) reported that copper nanoparticles can pass through the cell membrane and accumulate in cells; and at higher concentrations they can affect plant and root growth negatively.

Toxicity of Ag NPs is a serious problem to the environment, and seed germination and seedling growth of plants.

Originally produced by natural events, NPs have been present on earth for millions of years, but during the last decades, human activities have greatly increased the dissemination of NPs; for example, in air as ultrafine particles and in water and soil as colloids with an association of different particles. Figure 4 shows the mechanisms of NP-dependent toxicity. Also, several studies on the negative effects of different NPs in germination and early seed growth of forage and medicinal plants are shown in Table 4.

Figure 5 depicts a summary of the work carried out on effects of nano-priming on forage and medicinal plants. It considers two perspectives: (a) areas where some work on plant growth and development has been carried out, and (b) gap areas.

Various aspects of growth and development include seed germination, morphology of plants, plant growth, plant establishment, seedling viability and vigor, yield and performance of plants, chlorophyll, and photosynthesis and subsequently plant production. On the other hand there are a number of aspects that must be considered for future investigations, and these include: molecular, cellular, biochemical and genetics aspects of nano-priming, effect of nanoparticles on natural ecosystems, their impacts on animal and human health, introducing new and more compatible plant varieties to biotic and abiotic stresses, and nano-priming effects on increasing the active ingredients and essential oils of medicinal plants.

Conclusions and future prospects

In the age of modern technologies, there is a need for planted seeds to be healthy and germinate easily to produce strong seedlings that lead to better plant production. For this, some organic and chemical agents are used as priming to improve seed germination, and seedling growth and development. Extreme temperatures (hot and cold), salinity, drought and plunging are main challenges in forage and medicinal species planted under natural ecosystems and these abiotic stresses have similar effects at the biochemical, molecular and cellular levels.

Different researches have shown that seed priming is a smart and an effective choice, and it can be a possible tool to ameliorate germination, decrease seedling emergence time, increase seedling establishment and plant growth, survival, decrease time to flower, produce strong plant, ameliorate plants' tolerance to various biotic and abiotic stresses. Recent developments of seed priming, especially by using nanoparticles have been found to be very promising methods compared to the usual seed priming methods for seed germination and plant growth. For example, the ability of silver NPs to protect seeds from bacteria and fungi makes them potentially useful in gardening and other agricultural activities. Silica NPs improve the mechanical strength of leaves, light absorption, plant growth, enhancing photosynthesis capacity, endurance of plant organs and reducing evapotranspiration. Iron NPs are applied as nano-fertilizers to enhance accessibility of iron to plants, to control the antioxidant enzymes and phytohormone function, and to boost plant biomass, height, and root length. Titanium NPs help to increase seed water absorption, boost vigor of old seeds, prevent aging of chloroplasts, increase formation of chlorophyll, improve light absorbance, enhance

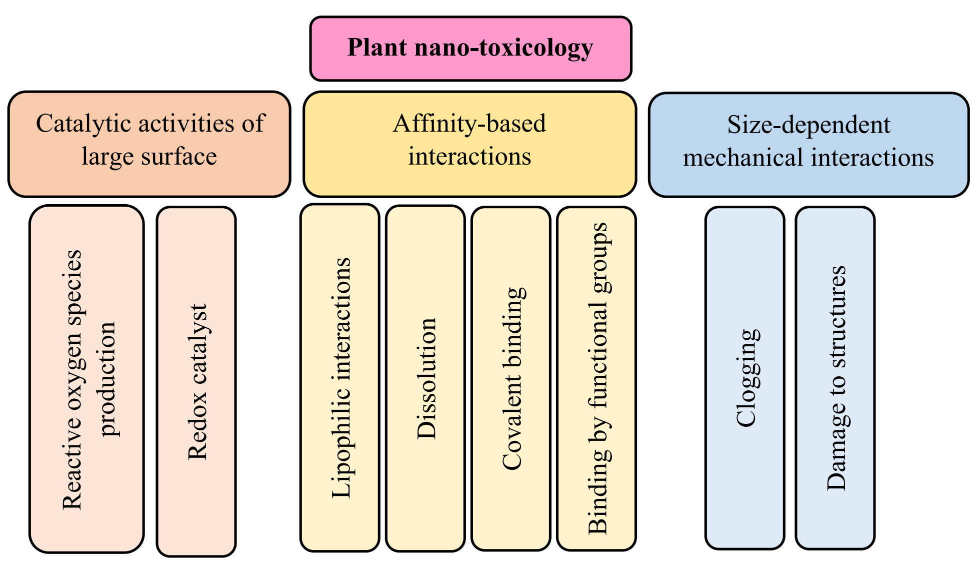

Fig. 4 Classification of NP-dependent toxicity mechanisms

Table 4 The negative (inhibitory) effects of nanoparticles on seed germination, seedling traits and plant growth of rangeland species

Nano-particle	Result (Negative effects)	Plant species	Usage		References
			Forage	Medicine	
Ag	Seed germination	*Brassica nigra*		✓	Amooaghaie et al. (2015)
	Shoot length	*Medicago sativa*	✓	✓	Ramezani et al. (2014)
	Root length; root and shoot dry weight	*Ocimum basilicum*		✓	Yosefzaei et al. (2016)
	Plant biomass; transpiration rate	*Cucurbita pepo*		✓	Musante and White (2012)
	Shoot and root length	*Linum usitatissimum* *Lolium perenne* *Hordeum vulgare*	 ✓ ✓	✓	El-Temsah and Joner (2010)
	Seed germination	*Arabidopsis thaliana*		✓	Lee et al. (2008)
	Root length and development	*Eruca sativa*	✓	✓	Vannini et al. (2013)
	Shoot and root length; seedling growth	*Sorghum bicolor*	✓		Lee et al. (2012)
Si–SiO_2	Shoot dry weight; root dry weight; plant growth; total biomass	*Secale montanum*	✓		Moameri and Abbasi Khalaki (2019)
	Root and shoot growth; total biomass	*Stipa hohenackeriana*	✓		Moameri et al. (2018b)
	Shoot elongation; shoot wet and dry weight; vigor index	*Guizotia abyssinica*		✓	Eskandarinasab et al. (2019)
Fe- FeO	Mycorrhizal biomass	*Trifolium repens*	✓	✓	Feng et al. (2013)
	Root and shoot length	*Satureja hortensis*		✓	Peyvandi et al. (2011a)
	Shoot and root length	*Linum usitatissimum* *Lolium perenne* *Hordeum vulgare*	✓ ✓	✓	El-Temsah and Joner (2010)
Cu–CuO	Photosynthetic performances	*Hordeum vulgare*	✓		Shaw et al. (2014)
	Root and shoot growth	*Lolium perenne*	✓		Atha et al. (2012)
	Nutrient content; enzyme activity	*Medicago sativa*	✓	✓	Hong et al. (2016)
	Root and bud growth	*Triticum aestivum*	✓		Lee et al. (2008)
	Seed germination; root and shoot elongation; plant biomass	*Elsholtzia splendens*		✓	Shi et al. (2014)
	Seed germination	*Zea mays*		✓	Zhang et al. (2015)
	Speed of germination	*Medicago sativa*	✓	✓	Ramezani et al. (2014)
	Plant growth; chlorophyll content; photosynthesis rates	*Arabidopsis thaliana*		✓	Wang et al. (2016)
Ti–TiO_2	Seed germination	*Vicia narbonensis*	✓		Castiglione et al. (2011)
	Plant growth; root development	*Panicum virgatum*	✓		Boykov et al. (2018)
	Root elongation; root wet and dry weight; vigor index	*Guizotia abyssinica*		✓	Eskandarinasab et al. (2019)

photosynthesis, and subsequently to increase plant growth and establishment. Although, some researches have shown the negative effects of nanomaterials on seed germination and plant growth, the magnitude of the toxic influences of NPs depends on the seed size, plant species, nanomaterial type, and the concentration of the NPs. As a new approach to modify the toxicity of nanoparticles, it is suggested that medicinal and forage species with known differences against various nanomaterials be planted.

The present study only dealt with the effects of different NPs on some of the most important characteristics of germination, morphology and physiology affecting the establishment and growth of forage and medicinal plants. While, the effects of the NPs on plants grown to maturity need to be investigated under controlled environment, field or field-like conditions also need to be considered to achieve a more realistic knowledge of the potential effects of NPs on key biotic and abiotic factors of the ecosystems involved, which consequently may have a deep effect on human health. Moreover,

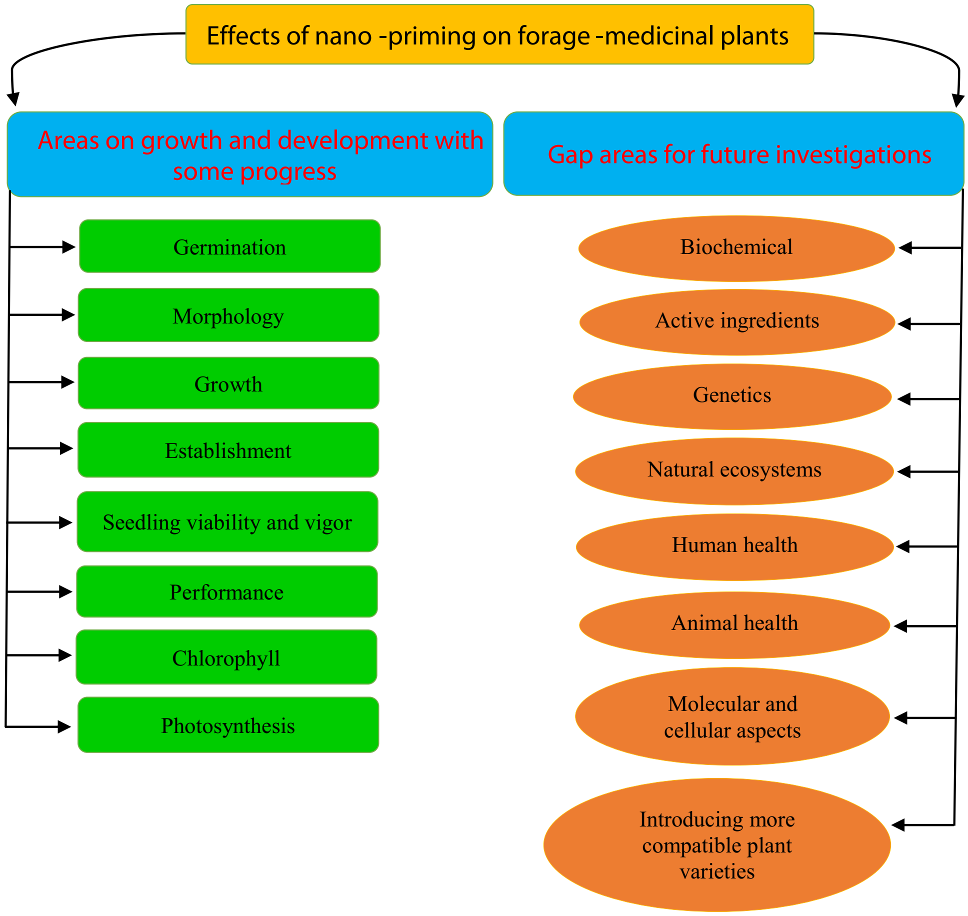

Fig. 5 A summary of broad areas on which some research work has been reported (green color) and areas for future research (gap areas; orange color) on forage and medicinal plants. (Color figure online)

previous studies have widely used agricultural and horticultural crops, while research on forage and medicinal and aromatic plants is quite recent and these less-considered plants require more consideration due to their valuable pharmaceutically properties. Nano-priming is effective in the early stages of germination and is likely to regulate DNA replication, translation and transcription. Therefore, it is necessary to study this topic and standardize the initial preparation methods in different products. In addition, further studies are necessary to provide more information about the impacts of NPs on gene up and down regulation, enzyme and protein accumulation in forage and medicinal plant cells. For maximum biomass and phytochemical production of these plants, optimization is needed. Defining optimal treatments in terms of NPs used, concentration and time of exposure to materials and their interactions on specific species and varieties under certain environmental conditions is necessary so that these technologies can help the expected production and cultivation of medicinal and forage plants. The introduction of new NPs to induction of new changes is needed for high positive effects and negligible toxicity. Furthermore, the effects of NPs on human and animal health and natural ecosystems should be studied.

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