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Review Paper

Nanotechnology and its potential application in forest and forest-based industries: a review

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ABSTRACT

Nanotechnology is an important and rapidly growing area of study and development, where a unique phenomenon offers innovative applications. Nanotechnology around the world is applied in various fields like agriculture, health, environment, forestry etc. In forestry, the technology provides solution to many forest-related problems and it is utilised for improving and protecting wood quality, extinguishing forest fires, successful seed germination, and effective herbal medication delivery. Some forest resources are also source of nanoparticles, which can also be used for further improvement of various forestry sectors. Although nanotechnology has significant potential in the field of forestry as an enabling technology, the future directions and requirements of applying nanotechnology in the forestry sector are still in their infancy, particularly in India. Therefore, this paper discusses the basic concept of nanotechnology and its potential applications both in forest and forest based industries. The paper also presents deep insights into the techniques of using nanotechnology for forest monitoring and management. Additionally, by merging biotechnology with nanotechnology, disease-resistant plant types, dormancy-breaking seeds, root-enhancers, and pathogen-eradication techniques can be developed. Nanotechnology may be applied on a large scale by facilitating technical and legal institutions, large R&D grants, and research collaborations in forestry research.

Keywords: Agriculture, forestry, nano-fertilizers, nanotechnology,

The existence of nanomaterials and nanoparticles in nature has been reported several millennia ago (Ghorbanpour and Hadian, 2017). Our ability to manipulate and create the intended nanomaterials and nanoscale objects changes as science and innovation advance at the microscale. It gives rise to a multidisciplinary subject known as nanotechnology that combines both science and technology to generate new and better materials with significant functional, physical and chemical properties. That means the technology involves the manipulation of materials with sizes ranging between 1to100nm (Wegner and Jones, 2006). When compared to the same materials with bigger dimensions, material at this size demonstrates unique features (Bajpai, 2016). But the fact that nanotechnology has both good and harmful elements has led to a split in the scientific community between those who believe it should be used for human welfare and those who do not. The crucial question is whether nanoparticles pose any danger or hazards. The utilised nanoparticles are anticipated to be found in the atmosphere, surface and groundwater, aquatic life, and terrestrial life, ultimately ending up in people. However, nanotechnologists, environmental scientists and researchers are not denying its deleterious effects on the environment and biological world due to the multifaceted fate of nanomaterials in the environment, despite the fact that nanomaterials also offer advantages in the environment (Singh *et al.*, 2021). In an assessment of current worldwide nanotechnology research, Kostoff and other scientists published their findings in 2007 (Kostoff *et al*., 2007). Similar reviews on the uses of nanotechnology in agro-ecosystems may be found (Baruah and Dutta, 2009; Mukhopadhyay, 2014; Bhagat *et al.*, 2015; Huang *et al.*, 2015; Manjunatha *et al.*, 2016; Elhawat *et al.*, 2018), among others. Due to their small size, it is predicted that nanomaterials would be able to readily pass through both human skin pores and the stomata and cuticle holes of plants. As a result, there are two groups of researchers on a worldwide scale: (a) those who believe strongly in the detrimental effects of nonmaterial factors on human and environmental health and (b) those that favour using technological applications in a good way. However, a definitive answer is still elusive, which has given researchers and scientists throughout the world the chance to study in this field (Singh *et al*., 2021). The potential for nanotechnology development has emerged during the past few years. Science's relatively young discipline of nanotechnology has a lot of room for future research and improvement. Numerous uses may be made using nanotechnology. Because they provide a number of chances to achieve exceptional material performance, nanomaterials have drawn a lot of interest.

Nanotechnology in forestry: Nanotechnology is an interdisciplinary applied science and technology subject that works with matter on the atomic and molecular scales, with sizes ranging from one to one hundred nanometers (nm) (McCrank, 2009). Nanotechnology is seen as advantageous owing to its distinctive features, such as: (a) the need for material and space (b) unique traits and prospective miracles (c) a fantastic length scale for productivity in creativity, etc. (Mohieldin *et al*., 2011). Nanotechnology around the world is applied in various fields like agriculture, health, environment, forestry etc. In terms of food, fibre, wood, oxygen, water, and earth chemical management, forests are the only community on earth where trees predominate. They also supply a wide range of products and ecological services. They are under tremendous strain as a result of the rise in demand for forest resources. An evaluation by the FAO for 234 nations and territories worldwide indicated a 3.3 Mha/year yearly decline in forest cover between 2010 and 2015 (Singh and Singh, 2019; Keenan *et al*., 2015). Foresters, scientists, and researchers from around the world are under pressure to provide practical solutions for the protection and management of forest resources due to the alarming rate of degradation. However, the ratio of supply (forest and resource production) to demand (human wants) is very low, necessitating the use of cutting-edge technologies like nanotechnology to maintain the ratio that is fundamentally needed to accomplish sustainability. Nanotechnology has exhibited its value in an array of fields, including plant behaviour research, forest management, harvesting, forest operations, creation of wood-based goods, use of these products for consumer behaviour research, etc. (McCrank, 2009). Furthermore, to address climate change challenges nanotechnology might be advantageous for the forestry industry (Singh *et al*., 2021). All facets of forestry and forest products, including trees, forest management, timber harvesting, forest activities, wood-based goods, and their uses, might benefit from it. By creating new goods and plant traits by applying nanoengineered catalysts, nanotechnology has also been proved to be useful in enhancing the energy efficiency of forests. Paper and pulp industry, packaging, agriculture, forestry, plant protection and nutrition, food, health, automotive, construction, sensors, and electronics are few examples (Qi *et al.*, 2013; Singh *et al.*, 2015). These applications are essentially still in the research and development stage, but a large market seems to be able to support their commercialization. The applications to which nanotechnology is applied greatly influence the likelihood of disputes over it. Despite its significance and promise in forest management, there are presently few studies of nanotechnology uses in the forestry industry.

Potential applications of nanotechnology: Following are the potential applications of nanotechnology in forest and forest-related paper and pulp industry as shown (fig. 1):

Alien species: The invasion of alien species, mostly in the form of weeds and scrubs, puts forests at danger (Newsome and Noble, 1986). The management of these invasive is difficult at ecosystem level. However, the reported studies have suggested that nano-herbicides can be used to manage them on a wide basis (Chinnamuthu and Boopathi, 2009).

Forest fires: The risk of forest fires is rising due to the thickness of the population, the slow growth of cities, attacks on the Wildland-Urban Interface (WUI) and changes in land-use plans that conflict with social and environmental guarantees. Rising temperatures and altering climatic patterns are exacerbating these issues (Singh *et al*., 2021). For this purpose, Fire Mesh, a proven nanotechnology solution, emerges in wildlands destroyed by forest fires with swift flame hiding, total smothering, and a speedy biological rebuilding influence. It provides protection from the fire for the surface that is in touch with the fire front by holding fast vertical surfaces. The Fire mash has the ability to put out a fire by eliminating both the chemical reaction and oxygen delivery to the fire (Singh *et al*., 2021).

Incidence of pest and diseases: Nowadays, the use of chemicals such as fungicides, herbicides and pesticides, and is the quickest and least expensive technique of managing pests and diseases. It is more efficient and ecologically beneficial to use pesticides in the form of nanoparticles and nanocapsules, and producing nanocrystals can make pesticides more effective so that they can be applied in smaller doses. Many nanomaterials, including iron oxide nanoparticles, polymeric nanoparticles, and gold nanoparticles, may be made inexpensively and used as pesticide or medication delivery gimmicks (Sharon *et al.*, 2010). Bhagat *et al.* (2013) used a low molecular mass gelator to convert the pheromone methyl eugenol (ME) into a nanogel. It has a high ability for crop protection and is ideal for management of pests in a wide range of crops. Electronic-nose devices have been used to detect tree diseases (Wilson and Lester, 1997), identify various microbiological pests that have a significant influence on the current health of forest stands, and determine if there are any hazardous insects in wood (such as termites) (Wilson and Oberle, 2011). Advanced optical sensors used in image analysis of plant symptoms provide visual validation of the condition of the plant's health as indicated by e-nose (Contreras-Medina *et al.*, 2012). Wilson *et al.* (2004) used e-nose technologies for the first time in plant pathology to diagnose tree diseases, as well as to find and identify wood decay fungi, the primary cause of wood rots in living trees (Wilson and Lester, 1998). Later study has illustrated the capacity of various e-nose equipments to recognise certain types of wood decays (Baietto *et al.*, 2010).

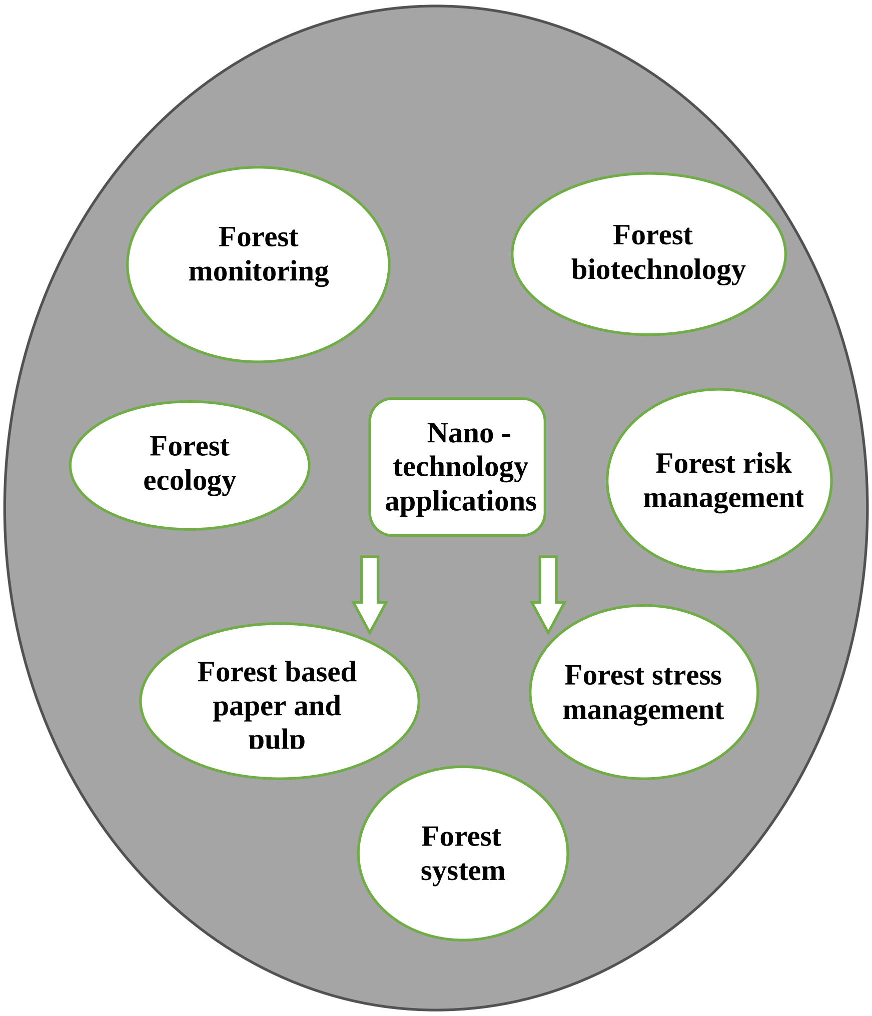

Fig. 1: Various forestry domains of current and potential applications of nanotechnology

Forest risk management: wastes: Metal particles created by nanotechnology are useful for reducing the danger of pesticide residues and industrial waste contaminating the environment (Chinnamuthu and Boopathi, 2009). This idea might be used to reduce the stress and danger caused by pesticides and herbicides in the lower stream forest system.

Fertilizer management: Globally, the widespread use of organic and mineral fertilisers has had a negative influence on water and soil quality (Bashir *et al.*, 2020). A novel method for improving the efficiency of nitrogen utilisation in crop production is to utilise nanofertilizers. Given that they may be administered in smaller amounts than conventional fertilisers, nanofertilizers have the potential to significantly improve environmental protection by lowering runoff, leaching, and gas emissions into the atmosphere (Adisa *et al.*, 2019; Manjunatha *et al.*, 2016). Several scientists have concurrently stated that the usage of fertilisers in both agro-ecosystems and forest systems may be improved by combining them with nano-clays and zeolites. Additionally, by releasing fixed nutrients into the soil, it improves soil fertility (Xiao *et al.*, 2008). They concluded that adding humic acid to the application of nano-fertilizer might improve the outcomes connected to an increase in growth. Therefore, nano-fertilisers are recognized as critical tools for increasing nutrient use efficiency, reducing fertiliser waste, and lowering cultivation expenses while improving crop growth, yield, and quality metrics. Nano-fertilizers enhance the surface area of the plant's numerous metabolic processes, which speeds up photosynthesis and increases the quantity of dry matter and crop yield. Crop growth is accelerated by nano-fertilizers to the highest concentrations. It also prevents plants from a various abiotic and biotic stressor (Singh *et al*., 2017). By providing a steady and continuous delivery of nutrients, nano-fertilizers can increase NUE (Nitrogen Use Efficiency) and aid in nutritional plant absorption. There is also debate about the price of manufacturing nano-fertilizers in comparison to traditional fertilisers and the size of the potential disruption to the current conventional fertiliser sector (Dimkpa and Brindraban, 2018). Using nano-fertilizers instead of traditional chemical fertilisers can enhance agricultural output by up to 30%, according to research (Jyothi and Hebsur, 2017; Kalia and Sharma, 2019).

Forest stress management: Abiotic variables, edaphic factors, pathogenic causes and global changes like global warming can all be stressors for forests (Sharma *et al*., 2017).The method of using nanotechnology to regulate plant stress, including the detection and signalling of stress factors such as abscisic acid (ABA), calcium ($Ca2+$), methyl salicylate, reactive oxygen species (ROS), nitric oxide (NO) and others (Singh *et al*., 2021). Nanotechnology-based nanobiosensors have the capacity to detect early signs of stress linked to nutrient shortages, plant diseases, soil moisture stress, etc. (Yao *et al.*, 2009; Chartuprayoon *et al.*, 2010; Singh and Singh, 2018; Wang *et al.*, 2018). Handheld devices' data may be varied to get hyperspectral readings, which can reveal details about the levels of chlorophyll, nitrogen, and plant diseases (Khan and Rizvi, 2014; Singh and Singh, 2018; Wang *et al*., 2018). Nanosensors have a minute degree of sensitivity that allows them to detect microbes, humidity and toxic contaminants. These techniques are frequently used in farming to improve crop output, disease resistance, etc. (Baruah and Dutta, 2009). According to research, engineered nanomaterials (ENM), in particular nanopolymer coated seeds, have the potential to withstand water stress and sprout under ideal circumstances. The arid regions with very little rainfall and water availability might benefit from this process of regreening (Dorraji *et al*., 2010; Su *et al*., 2017: Giraldo, 2019).

Forest monitoring: For effective forest management, it is critical to monitor the extent, condition and ecological functions of the forest. To collect exact data on soil, crop, weather, and environmental factors, modern forestry employs a wide spectrum of sensor equipment. Forest product production in various sectors uses sensing equipment for a wide range of purposes, including quality control and process monitoring. Moreover, in order to monitor forests and hazards associated with them, such as the effect of air pollution on forests, pathogen assault, etc., rapidly and on a broad scale, it is increasingly essential to use satellite and space technologies. Materials created via nanotechnology engineering are utilised to create sensors that measure how the earth's characteristics react to air pollution, light, moisture, etc. (Singh and Singh, 2019). The method could also be useful for creating sensors for satellite- and space-based applications such as remote forest monitoring. These sensors might be installed in satellite platforms or spacecraft or stations, giving them the capacity to estimate trace gases and contaminants and the impact they have on the health of the environment and the crew. Additionally, these may be used to determine which species in the forest are most tolerant to high levels of air pollution. Additional uses for the species screened under this category include creating green belts and reducing urban air pollution (Sharma and Sharma, 2018). Monitoring physical measures that are indications of the health of certain trees is the main goal of physiological measurements. Tree sap-flow sensors are essential instruments for determine the physiological condition of forest trees in order to spot drought conditions and gauge wood moisture content (Davis, 2012). These sensors use heating probes and cylindrical thermocouples to calculate plant transpiration. Making decisions on how to manage forests, such as determining when to harvest trees, require the use of this knowledge. Making scientific management strategies for the forests is made possible by current knowledge on the health of the forests (Singh and Singh, 2019). Applications of nanotechnology, as stated by the National Aeronautics and Space Administration, may help with this (NASA). Chlorophyll content, nitrogen content, and plant diseases are essential markers of forest health, and information from hyperspectral devices such as Hyperion-EO1, Advance Visible Infra-Red Sensor (AVIRS and its new generation), etc. (Khan and Rizvi, 2014; Singh and Singh, 2018; Wang *et al.*, 2018). Aerial remote sensing, greenhouse environmental sensors, portable field weather stations, electronic noses, biosensors and electrochemical sensorsare all used extensively in agriculture and forestry management operations (Li *et al*., 2010).These sensors may also provide species distribution across a vast region, which can be utilised for species-level forest management (George *et al*., 2014; Singh and Singh, 2019).

Forest ecology: Nanoscale sensors have been developed by researchers to solve issues with climate change in the forestry sector (Yadav *et al*., 2014). Carbon nanotubes (CNTs) and other nanotechnology-enabled biosensors, such as surface acoustic wave (SAW) devices, quartz crystal microbalance (QCM) devices, and ion-sensitive sensors (ISEs), may offer the chance to measure and estimate parameters that can be used to account for the ecological services provided by forests at the micro-level (Kaushik *et al*., 2015). These micro-level data are helpful for analysing how plants and the forest system are influenced by climate change (VanZee *et al.*, 2009; Yadav *et al.*, 2014). Researchers at the Coweeta Hydrologic Laboratory (Coweeta) have announced that a recently built resource, the Remote Assessment of Forest Ecosystem Stress (RAFES) network, would use RAFES stations to offer real-time updates on risk associated with forest ecosystems on a finer scale.

Forest-based paper and pulp industry: The ability to create wood and forest-based products using nanotechnology may surprise the forest-based economy (McCrank, 2009).Wood has a beautiful appearance. The mechanical qualities of wood are one of its most significant characteristics. These characteristics are crucial whether the forest product is a sheet of paper, a corrugated container, a composite, an engineered wood product, or solid wood (Moon, 2008). Table 1 lists some of the top forest-based sectors in the world that employ nanotechnology on an industrial basis. According to the investigation by Mohieldin *et al.* (2011), cellulose and lignocellulose have the ability to be used as nanomaterials because of their renewable nature, nanofibrillar structure, capacity to self-assemble into specific architectural forms, and multifunctional properties. Their research demonstrated good outcomes when using nanotechnology to create cellulose nanofibers via electrospinning, chemical treatment, and mechanical isolation. They said that the usage of nanomaterials, such as nano-dimensional cellulose fibrils, is necessary for the production of novel wood goods and products.E-nose devices play a variety of critical functions in the forest products manufacturing industry. Quality control (Wilson, 2011), industrial processing controls, particularly for observing biochemical and chemical processes in order to change machinery controls (Zondevan *et al*., 1999; Navratil *et al*., 2004; Lorenz *et al*., 2009), are all applications of e- nose in the production of forest products.

Paper and pulp: The main output of the forest is paper and pulp. Since a very long time ago, humans have made substantial use of paper in their daily lives. Important agreements, the Vedas, and scientific texts are regarded as valuable resources for the advancement of humanity. However, because of the characteristics of paper, including its hydrophilicity, fibrous architecture, high porosity, UV radiation-based disintegration, microbial assault and rapid water vapour transport (Richardson and Grubb 2013; Yang *et al*., 2013), its preservation from moisture, dust, and biological agents is a severe problem. In this regard, nanotechnology has significant potential and may offer a special chance to preserve and protect paper against deterioration caused by factors including moisture, light, temperature, dust, and biological agents. Table 2 lists the typical nanoparticles used in the paper industry along with their corresponding uses. Researchers and scientists have used nanostructured materials to create durable paper.Smart paper is electrically conductive, according to Agarwal *et al*. (2006), who also investigated a technique for layer-by-layer nanocoating lignocellulose microfibers to get a regulated conductive coating. The conductive paper is currently stable and used for longer than six months. Some potential uses of nanotechnology in the paper industry are: the creation of new materials; the use of nanofiltration to stop water circulation; development of coating materials and production of nanoscale assemblers are also included (Puurunen and Vasara, 2007). Nanoscale cellulose fibres may be created in four (4) different ways: (1) biosynthesis of cellulose nanofibers by bacteria (2) electro-spinning to create cellulose nanofibers (3) The manufacture of nanorods, commonly referred to as cellulose whiskers, and (4) microfibrillated cellulose plant cell fibre (Mohieldin *et al*., 2011). It has been discovered that nano-engineered fibre compounds and products hold promise for producing paper goods with exceptional strength.

Wood laminates: A potential application that can be used in forestry is nanocomposite laminates.

Wood preservatives: A copper nanoproduct for wood preservation was recently developed and distributed in North America. Matsunaga *et al*. (2007) compared the micro distribution of copper in the copper nanoparticle product to that in the standard wood preservation treatment. When combined with water-insoluble pesticide compounds, nano emulsions are very effective in pesticide formulations (Wang *et al*., 2007). It used to be a staple of the forestry industry to treat southern pine wood for preservation using chromated copper arsenate (CCA) (Laks and Heiden 2004). Heiden *et al*. (2005) investigated the application of nanotechnology in the sequestration of copper and organic biocides in wood. Concerns were raised regarding the risks its use posed to the environment and to human health. Although biocides with a lower solubility can irritate human skin, modern organic biocides have a higher environmental safety rating than

CCA (Yang *et al*., 2006). A product that offers a technique for applying organic biocides to wood without irritating it was proposed by Laks and Heiden (2004). Currently, wood is preserved and treated with sealants, varnishes, and laminates as well as an antimicrobial paint with silver nanoparticles is created, and it may be used to cover polymeric, glass, steel, and wood surfaces (Kumar *et al*., 2008).

Table 1: Forest based industries are involved in applying nanotechnology.

S. No.	Industry name	Country	Nature of works/remarks
1	US forest service products laboratory	US	Development of cellulosic nanomaterials, Published a total of 208 research articles during the year 2005 to 2016
2	Stora Enso Ltd.	Helsinki, Finland	Renewable solutions in packaging, biomaterials, wooden constructions and paper
3	Georgia Tech	Atlanta GA	Creating new materials by manipulating nanometer-length atoms, molecules, and supramolecular structures for improving construction and performance of devices in healthcare, electronics, and environmental management industries, Education and R&D in nanoscience/nanotechnology
4	Grenoble INP-Pagora	Grenoble INP-Pagora	Microelectronics, optical devices and telecommunications for scientific research Education and R&D in nanoscience/nanotechnology
5	Melodea Ltd.	Faculty of agriculture-Hebrew university, Rehovot,	Extraction of Cellulose Nano Crystals (CNC)
6	Nippon paper Industries Co. Ltd.	Japan	Research in cellulose nanofiber Environmentally-friendly biomass material
7	SUNY-ESF	United States	Environmental nanotechnology
8	Oji Paper	Tokyo, Japan	Paper and Packaging Industry, It has office in Rajashtan, India
9	Polynew, Inc.	USA	CNC development, Development of polylactic acid (PLA), an environment friendly bioplastic with potential to displace about 1 million pounds of volatile organic carbons (VOCs) per year
10	Daicel Chemical Industries, Ltd.	Japan	Developed Nanodiamonds which can be applied like other nanomaterials such as nano-silica, graphene, carbon nanotubes, fullerenes, and carbon nanohorns. It can be used as break-in additives for lubricants, grain refining agents, antioxidants, diamond sensors. Can be used in drug delivery, bio imaging

Forest biotechnology: Biotechnology is the process of expanding services and goods by utilising biological knowledge and technologies to modify molecular, genetic, and cellular processes. It is used in a range of areas, including agriculture, health care, and forestry (Fakruddin *et al.*, 2012; Prasad *et al.,* 2014). Additionally, nanotechnology speeds up the process of transferring genes from foreign creatures by enabling the site-specific transfer and expression of the desired product's or character's genes (Kuzma and Verhage, 2006; Maysinger, 2007; Scott, 2007; Chinnamuthu and Boopathi, 2009; Giraldo *et al.*, 2019).

Table 2: Nanoparticles commonly used in forest-based paper and pulp industries and their respective functions

S. No.	Nanoparticles	Functions
1	Nano-Engineered calcium silicate	Acts as paper filler, capacity enhancer, retains printing ink for long time
2	Nano-Silica	Downs the water transmission rate, protect against fungal infestation, reduce decay due to UV radiation
3	TiO_2 (Titanium dioxide)	Improves the optical properties such as opacity, whiteness and refractive index of the paper
4	TiO_2/ZnO (coupled Titanium Dioxide and Zinc Oxide)	Provides anti-parasitic property to Paper, reduce the effect of UV radiation, Increase the life of paper
5	Nano-cellulose	Used as packaging material due to less biodegradability, light weight and fewer environmental effects

Nanotechnology and forest biotechnology work together to improve performance. One important outcome of nanotechnology use in the forestry sector is the creation of disease-resistant variants of diverse plant species (Elhawat *et al*., 2018). Silver nanoparticles (AgNPs) that have been hormone stabilised, or "nanobullets," can both strengthen the root system and function as a pathogen killer on the target location. These nanoparticles also lessen the build up of hormones and silver in the plants, limiting negative consequences (Thangavelu *et al*., 2018; Thangavelu *et al*., 2019). Pests have the potential to seriously harm wood goods as well as the economy that depends on them. The forest sector would greatly benefit from a wood-based product that is pest-resistant. A product that can boost the present pest-resistance method would also be helpful. Seed dormancy has a significant impact on seed germination efficiency, which in turn has an impact on plant population. AgNPs, or silver nanoparticles, are a potent catalyst for releasing seeds from dormancy. Polymer coating in sesame (*Sesamum indium*) indicated that seeds covered with 4 g kg-1 polymer enhanced germination to 89 percent, followed by seeds coated with 3 g kg-1 polymer (87 percent) (table 3). Other characteristics such as shoot length, root length, vigour index and dry matter production, were also greater in polymer-coated seeds at a rate of 4 g kg-1 seed (Suma and Srimathi, 2014).

Table 3: Polymer coating's impact on seed and seedling quality traits

Polymer concentration @ g Kg-1 seed	100 Seed weight (mg)	Germination (%)	Root Length (cm)	Shoot Length (cm)	Dry matter production 10 seedling-1 (mg)	Vigour Index	Electrical conductivity (dSm-1)	Germination after 4 months (%)
3	305	87 (68.87)	13.0	6.2	45.0	1670	0.13	84 (66.42)
4	305	89 (70.63)	13.8	6.3	49.5	1788	0.10	86 (68.03)
5	306	86 (68.03)	12.8	6.0	47.0	1616	0.09	85 (67.21)
6	307	84 (66.42)	12.6	5.9	40.0	1554	0.07	83 (65.65)
Control	304	80 (63.43)	8.10	5.2	37.1	1064	0.08	75 (60.00)
CD (p=0.05)	NS	(1.819)	(1.118)	(1.123)	1.909	1.694	0.019	1.873

CONCLUSION

A young and developing area, nanotechnology uses nano-sensors, nanoaccumulators, nanostimulators, nanoabsorbers, nanoinhabitors, nanobiopesticides, nanofartilizers, and nanoparticles in a range of fields, including medical, agriculture, food, and others. In the field of managing forest resources, the potential of nanotechnology is slowly coming to light. Major areas of forest management, including forest risk management, monitoring, the production of paper and pulp from forests, the development of forest biotechnology, and forest ecology, are currently being examined. This has been shown useful in managing forest risk by identifying harmful contaminants at a microscopic level in plants, water, and air. Sensing devices based on nanotechnology have also been used to evaluate heavy metal levels and nutrient deficiencies in plants. Although the paper and pulp industry use nanotechnology extensively, the technologies now in use are not cost-effective enough to be scaled up or employed for commercial purposes, therefore additional study is needed. Additionally, by merging biotechnology with nanotechnology, disease-resistant plant types, dormancy-breaking seeds, root-enhancers, and pathogen-eradication techniques can be developed.

The applications of nanotechnology and nanobiotechnology in the agriculture sector have the ability to be expanded into the field of forestry due to the similarities in their microclimates. Through their ability to cause nanotoxicity, engineered nanoparticles (ENPs) can disrupt agricultural and agroforestry systems, altering their molecular and physiological properties. In order for research to be effective, awareness must be raised in both the nanotechnology and nanotoxicology fields. To secure and sustain the expanding research opportunities in the field of uses of nanotechnology in forest management, future opportunities in this area will be found in significant R&D grants, an increase in the number of technical institutions, and strong research collaborations with reputable labs. The production, use, and effects of different nanoparticles are being tracked by scientists. This is done to strike a balance between the advantages of the procedure and any potential negative effects.

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