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Review Article

Nanotechnological Interventions for Climate Change Mitigation: A Review

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ABSTRACT

Nanotechnology was the novel invention of the 20th century with wide applications in various fields making it the most promising technology of the future. World's focus is now towards sustainable development. Nanotechnology with its unique properties (smaller size, large surface area, high efficiency, gradual action, sensor ability, monitoring capability) made it the most inevitable tool in conservation of natural resources and mitigation of climate change. Agriculture sector contributions to the greenhouse gases (GHG) has been significantly increasing especially nitrous oxide emission from the applied nitrogenous fertilizers. Transportation, Energy and Industrial sectors are also in the race of adding GHG to the atmosphere. There are various reports saying that 1.5°C temperature increase over normal will reach by 2030 which is sooner than the predictions made by IPCC (Intergovernmental Panel On Climate Change). Though lot of research work has been going on with respect to climate change, still there are unexplored areas of nanotechnology applications. Nanotechnological interventions can play a role in the climate change mitigation. Hence this review made an effort to analyse and synthesise the applications of nanotechnology such as nano fertilisers and pesticides, nano coatings, nano fuel cell and batteries, nano sensors, nano blended fuels, nano structured materials etc. in greenhouse gas emission reduction and climate change mitigation for environment sustainability.

Key words: Nanotechnology, Climate change, Greenhouse gas emissions, Nano catalysts, Nano batteries

Introduction

Major force driving to climate change today is global warming. In 2014, Intergovernmental panel on climate change (IPCC) reported that scientists were more than 95% certain that global warming is mostly being caused by increasing concentrations of greenhouse gases. Each new decade is comparatively warmer than the previous one (IPCC, 2021). The anthropogenic influence on climate change is clear as the greenhouse gas emissions are increasing from food grain production for feeding the growing population (Bhatia *et al.*, 2010). India pledged to become carbon neutral by 2070 at COP 26 which was held at Glasgow of Scotland. Even COP 27 of Egypt emphasized the funding support to the developing countries from the developed countries to mitigate climate change. India being a developing country with second highest population in the world needs to focus on sustainability options in each and every sector. Agriculture is the main occupation of Indian subcontinent and also primary contributor to the N_2O which is 310 times more powerful in warming the atmosphere than CO_2 (Pathak *et al*., 2014). 60% of the GHG emissions is from energy, industry and transportation sectors (IPCC, 2019). Nanotechnology is the understanding and control of matter at dimensions between 1 and 100 nm where unique phenomena enable novel applications (National Nanotechnology Initiative). Nano-

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technology is one of the best solutions for the climate change related problems (Chousali *et al.*, 2023). From the production of food crops, their processing and transportation, and their disposal, there are many applications of nanotechnology. Even in construction of buildings, climate monitoring, waste management and capture of already emitted pollutants, the need of nanotechnology is there. The nanotechnological interventions can lead to counter climate change impacts and result in productive agriculture and sustainable ecosystem. Various approaches to address emerging threats under climate change are depicted in Fig. 1.

Reasons for choosing nanotechnology

Since the advent of 21st century, research on nanotechnology to reduce the pollution and climate change was increased manifolds. Nanotechnology helps to produce nano particles that has very low surface area which promotes faster reactions, faster reactions increase the efficiency and less consumptions of inputs, this less consumption will further lessen the emissions. Nanotechnology helps in providing alternatives to fossil fuel and thereby reducing greenhouse gas emissions (Rai *et al.*, 2016). Due to its reduced surface area, nanoparticles, catalyze the reactions at much faster rate and absorb the pollutants much efficiently (Mehndiratta *et al.*, 2013). Nano scale filters even remove the toxicants and pollutants from the fuel (Ibrahim *et al.*, 2016). Nanotechnology also helps to reduce emissions in vehicles by reducing their weight (Shafique *et al.*, 2019) and also helps in converting carbon into useful products (Ashley *et al.*, 2012). It also used in water treatment processes, reducing wastes into useful fuels thereby reducing chemical inputs into the environment through the use of carbon nanotubes, nano catalysts (Chyne *et al.*, 2022). There are many fields related to environment, agriculture, transport sector, etc. wherein nano technology has numerous applications (Table 1). Nanotechnology may bring another revolution in agriculture, industry and energy related fields.

Nanotechnology interventions to combat climate change

Nano fertilizers

It is known that modern agriculture requires large amount of chemical inputs compared to traditional/

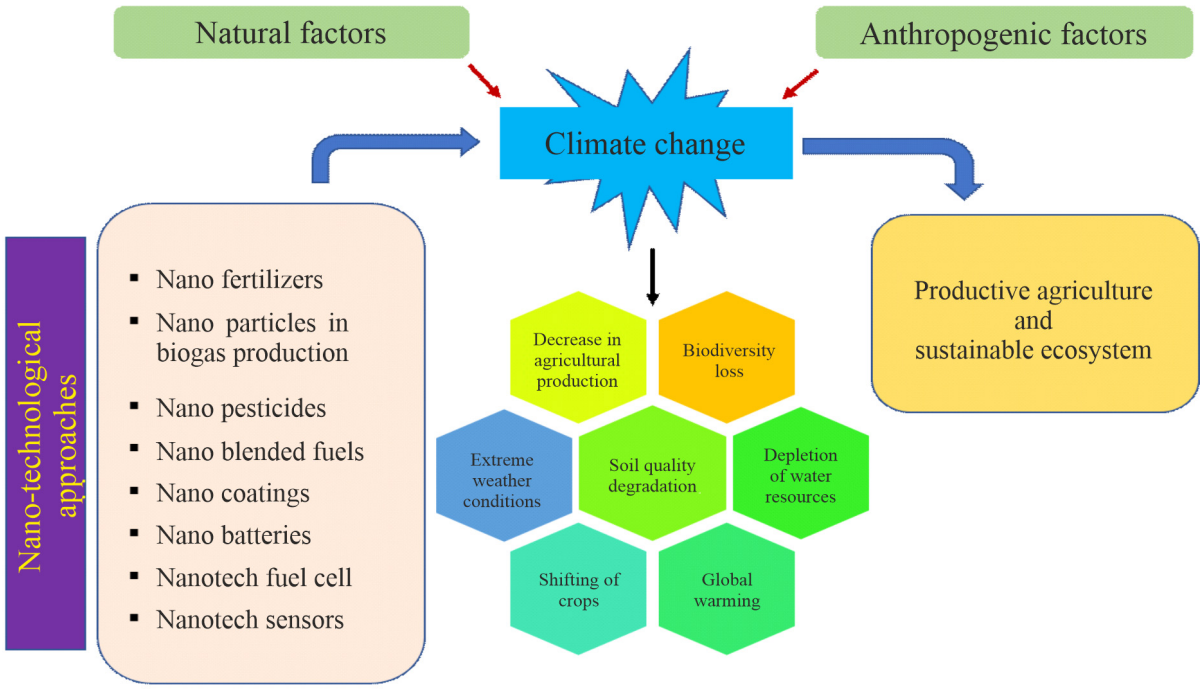

Fig. 1. Nano-technological approaches for climate change mitigation and adaptation

Table 1

Uses	Nanomaterials	Benefits
Nanofertilizers	Nanoparticles, nanoclays, nanocomposites, nano coatings, nano chelates, nano complexes and nano hydrogels	Prevent nutrient losses Increased nutrient use efficiency Efficient and slow release of nutrients Absorption of moisture and water retention capacity
Nano pesticides	Nano encapsulations (insecticide, herbicide, fungicide, biopesticides), controlled release formulations (solid, liquid and gaseous), nano adherents and adjuvants	Controlled release of active ingredients Prolonged protection Targeted delivery Eco friendliness Reduce the development pesticide resistance Better coverage and penetration
Nano particles in biogas production	Zero valent iron particles, nanocatalysts, corrosion resistant materials, nano based purification, nano membranes and nanosensors	Enhance the breakdown of organic matter Accelerate the digestion of matter Better resistance to corrosion of bioreactors Higher quality and yield of biogas Real time data from the sensors Separation of gases by using membranes
Automotive	Nano composite materials, carbon nanotubes, nano coatings, nanosensors, nano fuels, nano catalysts, nano fluids and energy storage via lithium batteries	Making the vehicles lighter More resistant to wear and tear Less fuel consumption Reduced carbon emissions Better heat transfer mechanisms Higher storage capacity of batteries
Renewable energy	Carbon nanotubes, quantum dots, graphene, nano wires, nano coatings, nano generators and nano solar cells	Conversion efficiency Corrosion resistance turbines and cells Better storage capacity Improved light absorption Better transmission
Environment	Nano filters, nano catalysts, nano sensors, graphene, metal oxides, carbon nanotubes and nano membranes	Water purification Air purification Conversion of more harmful pollutants into less harmful ones Environmental monitoring on real time basis Efficient CO_2 capture and storage

Conventional type of agriculture. Mechanization of agriculture also resulted into greater emission of GHG. Agriculture sector contributing 35% of the GHG emissions in developing countries (Tubiello *et al.*, 2022). Nano technology is the sustainable option to reduce the emissions and to improve the crop nutrition (Jakhar *et al.*, 2022). Nanofertilizers (NFs) are powder or liquid formulations which involve the synthesis, design and use of materials at the nanoscale level (Raimondi *et al*., 2021). NFs cannot be made in granular form due to their small size hence at the extreme solidness, it could be of powder form. There are many advantages in using NFs over conventional fertilizers. NFs reduce the losses and enhance the nutrient absorption by the plant by regulating the availability of the fertilizer in the soil (Verma *et al.*, 2022; Marquez *et al.*, 2022). NFs composites contributed to significant increase in the growth and grain nutrient content (Guha *et al.*, 2022). Less nitrous oxide emission recorded in nano zinc oxide coated fertilizers (Nagargade *et al.*, 2022). On the other side, Zn ions in ZnO NFs are heterogeneously distributed on wheat leaf as compared to $ZnSO_4$ treated samples through foliar application (Zhu *et al.*, 2020). NFs can easily penetrate through the stomatal pores and cell wall

(Fig. 2) (Hong *et al.*, 2021). Newly invented ZnO quantum out performed the nanoscale ZnO NPs in growth and nutrition of tomato (Sun *et al.*, 2023). This helps in better distribution of nutrients as well as suitability to foliar application as compared to conventional fertilizers. Nano particles increased the nutrient uptake by 58.30% and wheat crop yield by 22.13% (Sharma *et al.*, 2022). Application of Nano liquid urea may reduce the leaching, denitrification and ammonia volatilization losses (Kumar *et al.*, 2021). Because liquid formulations are mostly applied through foliar applications and no soil reactions are involved., thus have the added advantage in mitigating 100% soil emissions.

Macro nutrient fertilizers are usually coated with Zinc oxide nanoparticles (ZnO) due to its faster dissolution compared to the normal bulk ZnO (Milani *et al.*, 2012). 44.95% less N_2O emission was recorded by coating urea with 2% ZnO nano particles (Kundu *et al.*, 2016). Nano clay polymer composites (NCPC) helpful in reducing the N_2O emissions with the less amount of fertilizer and equal amount of yield in both rice and wheat crop compared to the conventional urea fertilizer (Kirti *et al.*, 2021). NCPCs are have a good water holding capacity and slowly release the fertilizers hence it's a viable method of application in agriculture (Saurabh *et al.*, 2019). Carbon nanotubes (CNTs) reduce the amount of chemicals released into the environment through targeted delivery of agro chemicals and reduce the damage to the plant tissue (Prasad *et al.*, 2017). NFs also enhance the abiotic stress tolerance i.e. drought tolerance in wheat plants (Astaneh *et al.*, 2021). NFs also deliver the nutrients in a controlled manner, so there will be a less water pollution by the use of such chemicals (Guo *et al.*, 2018). Thus, NFs are more sustainable as compared to conventional fertilizer.

Nano pesticides

Like nano fertilizers, nano pesticides are also available. Nano pesticides "involve either very small particles of a pesticide active ingredient (ai) or other small engineered structures with useful pesticidal properties" (Bergeson *et al.*, 2010). Right now, there are no evidences or research studies available on nano pesticides impact with respect to global warming but it has many benefits as compared to conventional pesticides. For efficient delivery of nano pesticides,

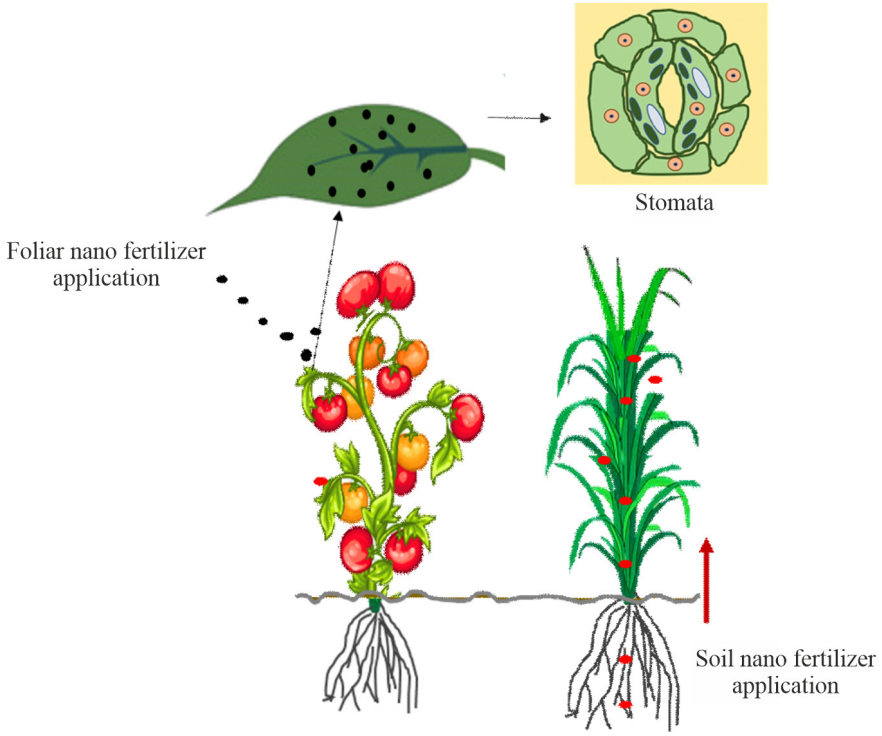

Fig. 2. Soil and foliar application of nano fertilizers in agriculture for combating nutrient deficiencies and climate change

Table 2. Impact of different nano fertilizers combinations on different crops in different regions of India

Crop	Nano fertilizers	Impact of nano fertilizer	Region of experiment	References
Paddy	Zinc nano particle (0-150 mg/l)	Increase in root and shoot length + biomass (fresh & dry)	Karnataka	Jyoti *et al.*, 2017
Paddy (Pusa basmati 1509)	Urea + magnetite nano fertilizer (Fe_3O_4)	Increase in yield+ brown head rice recovery (64.9%)	Punjab	Chitkara *et al.*, 2022
Sesame, mustard, wheat and pearl millet	Nano fertilizers of nitrogen & zinc + organic farming	Increase in the yield	Haryana	Kumar *et al.*, 2022
Maize	50% N+100% PK+ 2 sprays of IFFCO nano N with IFFCO sagarika	Maximum yield + disease resistance to turcicum leaf blight	Karnataka	Ajithkumar *et al.*, 2021
Foxtail millet	ZnO nanoparticles	Higher oil and total nitrogen content	Slovakia + India (Andra Pradesh)	Kolencik *et al.*, 2019

nano carriers are used which ensure pesticide stability against degradation and also micro fabricated xylem vessels are designed to understand the mechanisms involved in treatment of the diseases (Ditta *et al.*, 2012). If clay nanotubes are used in pesticides, 60-70% of the pesticide required will be reduced and cost of the pesticides also reduced (Murphy *et al.*, 2008). Even zero valent nano particles are used to remediate soil contaminated with previously applied pesticides, heavy metals and radionuclides (Mukhopadhyay *et al.*, 2014). This will directly lead to reduction in quantity of pesticide application, and thus indirectly contribute to impacts related to climate change.

Nano particles in biogas production

Bio gas production from biomass wastes or cow dung is like win-win idea to achieve sustainable goals. Nano particles (NP) acts as adherent or enzymes involved in biogas production are immobilized on nano particles, nano fibers and nano tubes through which anerobic process triggered by metal particles along with microorganisms to give biogas (Vasantha *et al.*, 2021). Enhancement of biogas production through anaerobic digestion using iron nano- particles is sustainable and feasible (Faisal *et al.*, 2018). Highest biogas yield noticed in iron oxide nanoparticles i.e., about 28% compared to nickel and cobalt nano particles in which 26% and 9% biogas yield was recorded (Zaidi *et al.*, 2018). Because significant enhancements in the growth of microalgae involved in biogas production was reported in all the doses of iron oxide NPs treatments (Rana *et al.*, 2020). Trace metals in the form of nanoparticles have a clear bio stimulating effect on the methanogenic activity during the start of the process as well as reducing the time required for biogas production till the end of the experiment (Abdelsalam *et al.*, 2017). Nickel nano-particles are able to effectively biostimulate the methanogenic bacteria and increase the activity and methane percentage (Dar *et al.*, 2021). Algae and microbial enzymes also have the ability to convert emitted greenhouse gases into useful industrial products like biofuel, biogas and bio polymers, but the efficiency is more when used with nano materials (Sharma *et al.*, 2022). However, cost effective synthesis of nano particles which are non-toxic to methanogenic organisms and environment are required (Arya *et al.*, 2021).

Light weight nano composite materials

Producing sustainable fuel or biofuel is one of the methods to reduce emissions, but making the vehicles even more efficient in using that fuel is needed. Metal components are usually adding weight

to any kind of vehicles hence to reduce weight, focus is shifted to various kind of nano- polymeric composites (Song *et al.*, 2012). Nano materials helps to produce automotive outer components in a very economical manner (Virmani *et al.*, 2021). 10% Reduction in weight of vehicle corresponds to 10% reduction in fuel consumption (Kawajiri *et al.*, 2020) and weight reduction also helps in fuel efficiency up to 4-8% (Fontaras *et al.*, 2017). Reduction in 100 kg weight of the vehicle is equivalent to the reducing 10 g of carbon oxide in atmosphere (De souza *et al.*, 2022). This shows the direct relation between weight of object and CO_2 emissions. This is because less energy is needed to accelerate the lighter object than the heavier one. Fibre glass carbon nano tubes helps in reduction of vehicle weight by 23% and thermal stability also improved by 5% (Subadra *et al.*, 2020). Graphene is another component which is made of layers of graphite also used widely in automotive industry and devices which are made by using graphene reduces 36% emissions of greenhouse gases (Cossutta *et al.*, 2021). Graphene nanoparticles used in fuel tank, carburetor, piping, tubing and injectors enhances the thermal and mechanical properties (Kiziltas *et al.*, 2021). Absorption of emitted greenhouse gases and its separation by using nano made materials like graphene oxide frameworks has been reported (Skarmoutsos *et al.*, 2017) and the graphene itself can be made using carbon naturally. Due to this it is both source and sink in itself.

Nano blended fuels

Many experiments are going on in and around the country to produce more efficient biofuel blended petrol and diesel to achieve fuel efficiency, reduce GHG emissions and mitigate climate change related impacts. Nano additives to diesel alone or biodiesel blends enhances combustion properties of fuel (Lv *et al.*, 2022). Biofuel blended conventional fuels tests shows 7.5% less emission of CO and 8.53% less emission of hydrocarbons (Agbulut *et al.*, 2022). Biodiesel with metal nanoparticles results in a complete combustion of fuel than the diesel alone (Hoang *et al.*, 2022). Because nano metals increase the engine performance. Complete combustion can be achieved by including cerium oxide nanoparticles which reduces the temperature of the carbon combustion and thereby improves the oxidation of the hydrocarbons (Norhafana *et al.*, 2020). Nano-catalysts mainly applied to improve fuel efficiency. Nano-catalysts uses the oxygen storing cerium oxide nanoparticles to promote complete fuel combustion, which helps in reducing fuel consumption (Zhang *et al.*, 2019). Nano-catalysts shows 8-10% savings in fuel consumption (Centi *et al.*, 2011) and it also reduces friction and improving wear resistance in engine. Nano-catalysts also a safer reagent to use in engine mechanics (Sancheti *et al.*, 2022). Nano catalysts in diesel- biodiesel fuel blends increase the performance efficiency parameters like power generation and fuel consumption (Mirzajanzade *et al.*, 2015). Only drawback is no known evidence is available to show the actual mechanisms involved in engine in presence of NPs.

Nano-coatings

Nano coatings are used in building constructions, vehicles manufacturing, solar panels etc. Nano coatings protect the buildings from excess heat and fire threat there by reducing greenhouse gas emissions and sometimes it is also used in advance fire warning systems (Zhu *et al.*, 2022). Nano coatings are introduced on photovoltaic panels which are hydrophobic in nature and also resistant to dust particles which enhance efficiency of the panels (Elnozahy *et al.*, 2022). To increase the absorption of solar energy, nano-black coatings are used in solar panels (Hussein *et al.*, 2023). Nano coatings are good way of reducing emissions and maximizing clean energy production (Hussein *et al.*, 2015; Christian *et al.*, 2013). Nano coatings can be applied to aircraft which can make aircraft smoother, reducing drag and also protect the material from extreme environmental conditions (Pathak *et al.*, 2020). Nano coatings also used for makings reflective surfaces to mitigate urban heat island (Wu *et al.*, 2022). Unlike normal metal coatings, nano coatings offer reflective and absorptive surfaces, corrosion resistant and dust proof surfaces, withstands all adverse weather conditions. This made the nano coatings a much needed and reliable tool in increasing efficiency and sustainability.

Nano structured materials

Nano structured materials are the novel materials like molecules, crystallite, clusters etc whose size

ranges from 1-100 nm (Omeiza *et al.*, 2023). Skyscrapers are most common in highly developed smart cities, warming effects are more felt in the urban areas compared to rural areas due to congestion and air pollutants traffic. Hence buildings should be constructed with materials having thermal insulating properties. Silica aerogel is the lightest solid material known with excellent thermal insulating properties of the buildings and also reduces the heat load on heating systems (Baetens *et al.*, 2011). Concrete production has high carbon footprint, due to carbon nanotubes -concrete composite, approx. 1000 ton of cement that is not produced avoids the emissions of over 800 tons of CO_2 (Nanowerk, 2019). Nano concrete improve the bulk properties of cement including faster setting time, thinner structural element and less consumption of cement (Olafusi *et al.*, 2019). Graphene is a thin layer of graphite which is ideal material to create chemical and gas filtration (Jirickova *et al.*, 2022) and reduce the carbon dioxide released from cement and concrete (Shamsaei *et al.*, 2018).

Improved renewables

India is now a global leader in taking initiatives with respect to enhancing the solar energy outputs to become carbon neutral and to follow the sustainable path of energy production. In this direction nanotechnology is essentially needed to enhance the efficiency of renewables and making India's dream of becoming carbon neutral country by 2070 into reality. Nanotechnology applied to photovoltaics, which is used to produce solar panel which doubles or triples the output (Ahmadi *et al.*, 2019). Graphene applications in photovoltaics industry is far beyond imagination (Mandal *et al.*, 2021). Nanoscale particles used in heat and corrosion protection layers for turbine blades in wind power plants to enhance efficiency by providing self-cleaning surfaces of wind turbine (Ahamdi *et al.*, 2019; Sharma *et al.*, 2018). Nanotechnology also make wind blades lighter in weight which enable the turbine blades to move even at slightest wind (Agboola *et al.*, 2022). Nano-coatings prevents the corrosion of blades and also enhance the shelf life of the Photovoltaic grids (Abdelsalam *et al.*, 2014). Nano coatings of black colour enhance the solar radiation absorption capacity of the panels. Hence nanotechnology has wide utilizations in renewable energy sector and can be the major focus for mitigation to climate change.

Nano-batteries

Nanobatteries are fabricated batteries employing nanotechnology at the nanoscale, particle that measure less than 100nm (Singh *et al.*, 2017). Nano-batteries are very advantageous compare to conventional batteries in various ways. Nanoparticles in the battery decrease the amount of strain and reduce the volume expansion (Szczec *et al.*, 2011). Due to increased surface area of the battery, lithium diffusion rate is very high compared to conventional batteries (Lee *et al.*, 2011). Reversible capacity of the battery is very fast and the battery can undergo many cycles without losing charge in case of sodium ion batteries (Nithya *et al.*, 2015).Increasing the available power from the battery, decreases the time required to recharge the battery hence electric vehicles with fast charging capacity can be achieved (Li *et al.*, 2017).Nano-coatings in the batteries also separates the electrodes from the any liquids when battery was not in use causes high level discharge

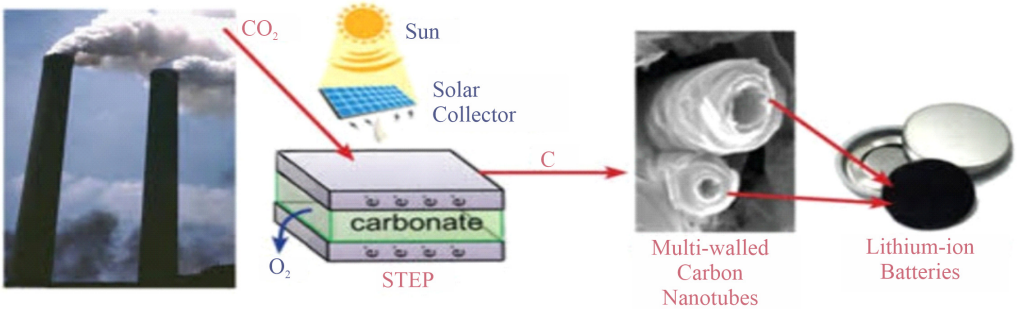

Fig. 3. Transforming ambient CO_2 into batteries through solar thermal electrochemical process (Stuart Licht *et al.*, 2016)

because of less interaction between electrode and liquid hence increase the shelf life of the battery (Weng *et al.*, 2022). Another important thing about nanobatteries is nowadays it is used to transform the carbon dioxide emitted from the industrial smokestack directly into the anode of the battery. Carbon dioxide from the industry smokestack is separated into carbon and oxygen by using STEP process (Solar Thermal Electrochemical Process). This carbon is used to make anode of the batteries which contributes to 40% of the battery making itself by using emitted carbon dioxide (Mallakpore *et al.*, 2021). Graphite electrode used in lithium ion batteries that power electric automobiles can be replaced with carbon material recovered from atmosphere. Carbon nanotubes produced from ambient carbon dioxide for environmentally sustainable lithium ion battery anodes (Piatek *et al.*, 2021).

Nanotech fuel cell

Fuel cell is a device that converts fuel directly into electricity through electrochemical reaction. In fuel cells hydrogen is most commonly used fuel, which is very costly and also difficult to produce and store. By applying nanotechnology hydrogen trapping and storing is very easy and efficient. Carbon nanotubes make this easier by absorbing and transporting hydrogen very easily (Hussein *et al.*, 2015). One of the electrodes in the fuel cell is made up of platinum which is very costly which makes the use of fuel cell limited. By applying nanotechnology instead of just using platinum, nano composites with platinum or carbon nanotubes alone are used which reduce the cost of the fuel cell (Dicks *et al.*, 2006). Nano-coatings in the fuel cell also increase the shelf life of the nano-tech fuel cell (Aithal *et al.*, 2016).

Nanotech sensors

Sensors are mainly used to detect the issues ahead of time. They are self-sensing and self-monitoring. Nano sensors do not need any wire connection and also cost effective way to know various parameters of climate and weather ahead of the time (Wilson *et al.*, 2004). Nano-sensors are mainly used to detect pollution and they have selectivity towards micro and nano pollutants (Hairom *et al.*, 2021). Some engineered sensors also used in waste water treatment to detect pollutants and remediation (Murshid *et al.*, 2021). Nano sensors also reduce the millions of tons of chemical which are dumped into the soil in the name of fertilizers and thereby reduce the amount of emissions from the soil (Thakur *et al.*, 2022). Due to their self-diagnostic capacity sensors can be integrated with the precision agriculture too. So that unsustainable exploitation of water, soil and nutrients can be minimized and this directly results in lowering the emission of greenhouse gases and adapting to climate change.

Concerns of nanotechnology

There are concerns regarding the bioavailability, safety, reactivity and toxicity of the released NPs. Researchers are also speculating on the working mechanisms of different approaches of nanotechnology. Sometimes NPs especially in the NFs results in compartmentalization of nutrients i.e. accumulation of NPs in the lower tissues of stomata which affects stomatal conductance, photosynthetic rate and transpiration (Cruz *et al.*, 2019). Many NPs also affects the soil microbiota and enzymatic reactions occurring in the soil for example silver NPs (Javed *et al.*, 2019). There is also concern regarding toxicological effects on human health and natural ecosystem with respect to nano pesticides. Apart from human health and environment concerns against the use of the nanotechnology, its other acute and chronic effects on biotic and abiotic environment are vague and need more research.

Conclusion

Nanotechnology applications can mitigate greenhouse gas emissions and enable adaptation to climate change. From agriculture to industrial production, nanotechnology can play a very important role in mitigating carbon dioxide equivalent emissions. The main climate change driver CO_2 can be successfully controlled by converting it into biofuels, CO and biogas. Engine efficiency, fuel purification, emission filtration, light weight vehicles and aircraft all will together help us to curb carbon emissions. Research in the area of nanotechnology

needs to be improved and proper infrastructure and production incentives to industries and government institutes is needed. Awareness should be created regarding nanotechnology applications in the climate and environment related fields. Financial assistance for the startups that are taking interest in the field of climate change mitigation through the use of nanotechnology should be provided. Sustainability of synthesis and manufacturing of nano materials or particles should also be taken into considerations, as nanotechnological procedures should not involve enhancing the emissions rather than curbing them. The implications of long-term use of nano materials on environment and organisms still needs to be studied in greater detail.

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