Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future

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Received: 16 February 2022 / Accepted: 28 March 2022
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Abstract
This review gives concise information on green technology (GT) and Industrial Revolution 4.0 (IR 4.0). Climate change has begun showing its impacts on the environment, and the change is real. The devastating COVID-19 pandemic has negatively affected lives and the world from the deadly consequences at a social, economic, and environmental level. In order to balance this crisis, there is a need to transition toward green, sustainable forms of living and practices. We need green innovative technologies (GTI) and Internet of Things (IoT) technologies to develop green, durable, biodegradable, and eco-friendly products for a sustainable future. GTI encompasses all innovations that contribute to developing significant products, services, or processes that lower environmental harm, impact, and worsening while augmenting natural resource utilization. Sensors are typically used in IoT environmental monitoring applications to aid ecological safety by nursing air or water quality, atmospheric or soil conditions, and even monitoring species’ movements and habitats. The industries and the governments are working together, have come up with solutions—the Green New Deal, carbon pricing, use of bio-based products as biopesticides, in biopharmaceuticals, green building materials, bio-based membrane filters for removing pollutants, bioenergy, biofuels and are essential for the green recovery of world economies. Environmental biotechnology, Green Chemical Engineering, more bio-based materials to separate pollutants, and product engineering of advanced materials and environmental economies are discussed here to pave the way toward the Sustainable Development Goals (SDGs) set by the UN and achieve the much-needed IR 4.0 for a greener-balanced environment and a sustainable future.

Keywords Green technology · Environmental biotechnology · Environmental economies · Bio-based materials · Sustainable transitions · Fourth Industrial Revolution · Post-COVID-19

Introduction
In today’s world of climate change and amid the COVID-19 pandemic, a realization has dawned upon the world to protect the planet and people’s health. The pandemic has affected many social, economic, political, and environmental challenges (McNeely 2021). There is a clear awareness about global environmental issues like global warming, acid rain, ozone layer depletion, the increasing list of endangered species, and incidences of forest fires in the Amazon. There have also been several protocols and agreements signed by the world’s governments, like the Kyoto Protocol and the Paris Agreement. However, even till now, proper actions have not been taken, and the governments have also not been able to engage people to follow and practice environmentally friendly habits daily.
Nevertheless, scientists have been relentlessly working to find solutions to create a sustainable future for the coming generations and save and conserve the environment. They are coming up with the latest innovations in GT, which can help industries find alternative and sustainable ways of disposing of waste and use more bio-based advanced materials for cheap, safe, and eco-friendly products. GT is a broad word that applies science and technology to lessen human impacts on the environment. Energy, atmospheric science, agriculture, material science, and hydrology are all areas of scientific inquiry covered by GT (Fu et al. 2021a, b). Several GTs strive to combat climate change by minimizing carbon dioxide (CO2) and other greenhouse gas emissions. Solar power is one of the most effective GTs. In many countries, it is currently cheaper to install than fossil fuels. GT can be supported by investing in stocks, mutual funds, and bonds that support ecologically friendly technology (Hou and Wang 2021).

The world has already witnessed three industrial revolutions (IRs), having significant impacts (Dogaru 2020). The 1st IR dealt with mechanical processes using water and steam for the mass production of textiles and metals. The 2nd IR dealt with the concept of industries, and here, the use of electricity, oil, and gas took place; the steel and synthetic industries became established with new communication and transport systems. The 3rd IR dealt with new nuclear energy and automation (Dogaru 2020). However, most of these revolutions had enormous consequences on the environment. They caused much damage and harm to the planet and human lives. Hence, the IR 4.0 is a viable, sustainable, and environmentally friendly approach to manufacturing, using renewable resources in stocks, mutual funds, and bonds that support ecologically friendly technology (Carvalho et al. 2018; Dogaru 2020). This revolution is necessary for the green recovery post-COVID-19 in terms of the green economy. Governments have taken steps to reduce carbon and other greenhouse gas (GHG) emissions, price the carbon externalities, and increase renewable energy resources like solar and wind energy (McNeely 2021). Nanotechnology has also been a significant contributor to GT, helping alleviate problems related to the agricultural, medical, food sectors, etc. (Bahrulolum et al. 2021). Nanoparticles can help develop biopesticides to improve crop production and enhance organic, eco-friendly farming methods (Bahrulolum et al. 2021). Nanomaterials, which are bio-based like nanocrystalline starch, lignin, and cellulose, can help improve the bioavailability of drugs and other nutrient supplements (Kou et al. 2021).

This review paper provides an opportunity to understand how to formulate and execute sustainable, eco-friendly goals at a social, economic, and environmental level. This includes—(i) a brief introduction to the global environmental concerns; (ii) in depth detail of environmental biotechnology, genetically modified organisms (GMOs) and their applications in bioremediation, biopesticides and more; (iii) methods of proper management of waste and polluted air treatment using renewable and nonrenewable energy resources with more focus on bioenergy and biofuels; (iv) study of renewable biomass-derived carbonaceous materials like cellulose, nanocellulose, chitosan, lignocellulosic residues and how using chemical engineering techniques can make sustainable, highly useful and eco-friendly products; (v) understanding the interaction of pollutants with the environment during separation processes using bio-based adsorbents, hydrogels, and membrane filters; (vi) in-depth information on production engineering and the types of bio-based advanced materials and processes; (vii) understanding process system engineering, the goals and the current research on IR 4.0 and how it can be made into a reality, and lastly; (viii) detailed understanding of environmental/green economies, how the post COVID-19 pandemic has led to more research and paved the way toward the green transition, the Green New Deal for a sustainable world, how can the governments price carbon externalities, how can an individual, community, industry, country, and the world shift toward sustainable transitions in their lifestyle, practices like green entrepreneurship, green housing, green chemistry, and understanding the critical concepts of ecological modernization, de-growth, and more. Understanding why people adopt GTs in different ways is crucial. Regardless of what we know about the elements that influence adoption, the willingness to accept new GT remains low. Cognitive, goal-oriented hope can help people adopt GTs sooner. Unlike socioeconomic variables, which are difficult to modify, legislation and education can influence levels of hope and motivation (Bukchin and Kerret 2020).

**Environmental biotechnology**

Climate is a mind-boggling combination of physical and natural environmental elements, including ecological issues like global warming, ozone layer depletion, biodiversity loss, exhaustion of regular assets, overpopulation. Presently, natural issues make us defenseless against tragedies and catastrophes. Biotechnology combines engineering design to utilize cells and molecular analogs for substances and their administrations. Carbon emission efficiency is essential for tracking progress toward carbon emission reduction goals. The link between GT innovation and carbon emission efficiency has not been well investigated, and the transmission mechanism is unknown (Dong et al. 2022).

Environmental biotechnology is an arising innovation regarding ecological insurance since quick industrialization, urbanization, and advancements have undermined clean climate and exhausted standard assets (Gavrilescu 2010). It tends to be considered the main thrust for coordinated
Environmental conservation, prompting a maintainable turn of events. Sustainable development characterizes progress in human prosperity that can be broadened or delayed over time. It requires a system for coordinating ecological arrangements and advancement procedures worldwide (Fig. 1) (Singh 2017) (Gavrilescu 2010). Green supply chains are logistical frameworks that ensure the environmentally friendly manufacturing and delivery of items worldwide. Companies must engage in the design and planning optimization of their logistic systems to reach this aim while considering the trade-off between earnings and environmental implications (Pinto-Varela et al. 2011).

**Industries and aspects of environmental control**

The late carried out aggressive task Clean Development Mission (CDM) by the Government of India, wherein clean innovation overall, white biotechnology, and specifically, GT can make significant commitments toward the supportable and sustainable development. The generated wastes should be dealt with appropriately before arranging the climate. Biotechnology’s devices and strategies have given a new impulse and opened new vistas in contamination control. Biosensors assume a fundamental part in distinguishing the toxins even at exceptionally low focuses on evaluating the danger level. The industry is the primary source of pollution in the environment. Industrialists must become aware of their environmental responsibilities in the new era. They should be ecologically conscious even if they are chief manufacturers (Mondejar et al. 2021; Lamba et al. 2021).

Modern handling commonly elaborates adversities like pH, temperature, and high pressure requiring high energy input, while microorganisms and catalysts ordinarily catalyze a similar cycle in mild conditions (Sharma et al. 2017). A broader and clear idea can be obtained by understanding the correlation between GT types with IR 4.0. Understanding the exact mechanisms of technologies like sunlight transport, plastic roads, plant walls, milk textiles, plant-based packaging, building-integrated photovoltaics can display their relation to IR 4.0 (Table 1).

Profoundly contaminated industrial wastewaters are ideally treated in an anaerobic reactor because of the high degree of chemical oxygen demand (COD), the potential for low surplus sludge generation, and energy production. In
| Types of GT       | Type of environment effected | Description                                                                 | Equipment involved                                                                 | Value                                                                 | Related concepts                                                                 | Relation to IR 4.0                                                                 | Mechanism involved                                                                 | Outcomes due to IR 4.0                                                                 | References                                                                 |
|------------------|------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| **Sunlight Transport** | Outdoor (source)            | It is a passive system that captures sunlight from an outside source. It transports it via fiber-optic cables to illuminate light-deprived rooms | Passive light collectors, heliostats, lighting rod, fiber optical system, daylight shading system, mirror light pipes, daylight guiding system | Zero utilization of energy during the daytime People might incline toward natural light | Light tube, Passive design, Translucent concrete, Smart glass                     | IR 4.0 in the sustainable energy industry gives smart energy networks that stay away from advancing new path reliance. The innovation will empower decentralization, with energy coming from local sunlight-based photovoltaics | A medium-scale, decentralized unit is connected by virtual power plants that generate power. Involves a cloud-based center, which controls IoT devices in the units | This implies that the user will control and manage their energy use          | (Mondejar et al. 2021)                                                      |
| **Plastic roads**  | Outdoor                      | Plastic roads are completely manufactured of plastics or composites of plastic with different materials | Soft foams, Hard foams, Films (carry bags, cups), Laminated plastics | In situ process No advancement of any poisonous gases like dioxin Less use of bitumen Plastic waste management | Flux sheets, polyvinyl chloride (PVC) sheets must not be utilized regardless | The IR 4.0 concerning the plastic processing process permits customers, suppliers, and the close interconnection of internal departments and processes | Each fundamental area of the economy, from agriculture to packaging, building development, and automobiles, has been virtually revolutionized by the uses of correspondence or InfoTech with plastics | Mass production of products began, and plastic appeared to be a less expensive further more effective raw material | (Mondejar et al. 2021) (Lamba et al. 2021)                                    |
| Types of GT | Type of environment effected | Description | Equipment involved | Value | Related concepts | Relation to IR 4.0 | Mechanism involved | Outcomes due to IR 4.0 | References |
|-------------|-----------------------------|-------------|--------------------|-------|------------------|------------------|-------------------|---------------------|------------|
| **Plant walls** | Outdoor as well as indoor | Vertically assembled structures hold sufficient soil to have various plants or different greens growing on them. Since these designs have living plants, they additionally highlight built-in irrigation frameworks | Water Nutrients Top reservoir Bottom reservoir Pump line Water pump Timer Drip emitters | Greywater treatment Low energy cost Recycling of household wastewater Temperature insulation of the houses Aesthetical value | Principle of hydroponics | Dominating energy requirement materials worldwide are concrete and stainless steel, which have increased since IR. The choice of materials decides the environmental effect of the building | Contingent upon the materials and with their substitutions across the helpful existence of the structure, the outcomes may be decreased in the entire life cycle | Sustainable-built environment Self-irrigation Architectural upgrade Customization Efficiency | (Mondejar et al. 2021) (Chàfer et al. 2021; Pradhan et al. 2019) |
| **Milk textiles** | Outdoor | Fabric made with casein present in milk. It has for some time been valued for its smoothness and softness | Skimmed milk Glutinous solution Micro-zinc ion | Skin nourishment Eco-friendly Biodegradable Renewable | Bio-engineering Bacteriostatic Zero-waste policy | The milk textile industry relies upon using advanced technology in production and logistic processes inside the system of technological headways arising because of IR 4.0 | Redesigning industrial processes as per IR 4.0, each process connected to logistics and production might be more flexible and rapid in textile value chains | Real-time information (variable customer requests) Optimal material flow systems Self-configuration | (Mondejar et al. 2021) (Malucelli 2019) |
| Types of GT              | Type of environment affected | Description                                                                 | Equipment involved                                                                                           | Value                          | Related concepts          | Relation to IR 4.0 | Mechanism involved | Outcomes due to IR 4.0 | References                  |
|-------------------------|------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|-------------------------------|---------------------------|----------------------|---------------------|-----------------------|--------------------------|
| **Plant-based packaging** | Outdoor                      | Uses sustainable organic and vegetal sources to develop the packaging       | Bio-based feedstock; polyester Sugars extracted from sugar-cane, corn, wheat, beet, agricultural residues | Degradable and recyclable (100%) Lowers carbon footprint Free of toxins and allergens | Polyethylene furoate (PEF) Compostable | IR 4.0 is the eventual fate of development and productivity in the packaging sector. It approaches things in other ways, introduces a high degree of connectivity and automation, and makes better use of big data | A cloud-based predictive maintenance platform can assist producers with distinguishing basic failures before they happen | It leads to a rise in overall equipment effectiveness and, as such, a fall in the total cost of ownership | (Mondejar et al. 2021) (Roy and Rhim 2021) |
| **Building-integrated photovoltaics** | Outdoor (source) Indoor | Photovoltaic materials are utilized to supplement traditional building materials in pieces of the structure envelope like the facades, roofs, or skylights | Facades (photovoltaic materials) Glazing Pitched roofs | Impersonate the appearance and capacity of ordinary roofing materials, while the key task is to generate electricity | Thin-film technology Short-circuit current Open-circuit voltage Fill factor | Grids draw on the possibilities of data and correspondence advancements to screen and effectively deal with the generation, conveyance, and utilization of power from various—possibly decentralized—wellsprings of electricity to fulfill the changing power needs of end clients | Airflow behind PV panels generates a cooling effect that helps produce significant energy with higher efficiency | Circular economy vision Sustainable and renewable electricity generation | (Mondejar et al. 2021) (Du et al. 2019) |
many applications, notwithstanding the proficiency of the anaerobic cycle being high, overall stabilization of the natural matter is not possible anaerobically because of the wastewater’s high degree of organic ability. The end product delivered by the anaerobic treatment contains solubilized natural matter. It is practical for aerobic treatment, demonstrating the capability of utilizing anaerobic-vigorous frameworks, and resulting posttreatment utilizing high-impact treatment (Chan et al. 2009).

**Genetically modified organisms (GMOs) in environmental biotechnology**

GMOs are also known as transgenic organisms. It is categorized as microbes or animals whose DNA has been altered by utilizing genetic engineering techniques to generate desired biological products. GM animals have even been utilized to develop human transplant organs and tissues; such a concept is known as xenotransplantation. The wide range of GMO applications gives people significant advantages; however, many individuals likewise stress over expected risks. Microbes and animals have all been genetically altered by different change strategies for quite a long time with agricultural, medicinal, ecological, and all the more as of late industrial purposes (Phillips 2008).

**Ralstonia pickettii**

*Ralstonia pickettii* is an oligotrophic, rod-shaped Gram-negative, oxidase-positive, aerobic, and non-fermentative ubiquitous microorganism found in soil and water.

*Ralstonia pickettii* has immense biotechnological significance in the bioremediation niche and has shown its capacity to break down many xenobiotic pollutants, such as trichloroethylene and toluene, which are released into the environment by different industrial methods. It is hypothesized that in ultrapure water frameworks, the microorganisms might have the option to scavenge from the polymers in plastic piping. Moreover, *R. pickettii* has been displayed to have biodegradative capacities, exhibiting its enormous metabolic variety. *R. pickettii* strain PKO1 could be super biodegraded with the presentation of plasmids bearing other degradative proteins, such as pKA4, and incorporating different qualities from various microorganisms into the chromosome to aid the breakdown of harmful compounds (Ryan et al. 2007). A few strains have demonstrated the capacity to persevere in high contaminations of metal-debased conditions. In an adverse environment, the ability to sustain *R. pickettii* is a contender for bioremediation (Huang et al. 2018) (Mijnendonckx et al. 2013). Fast adaptation of *R. pickettii* to elevated metal concentrations shows up because of vigorous gene duplication and importation of a few kinds of resistant determinants (Yang et al. 2010).

**Environmental biotechnology advances for a greener future**

**Bioremediation**

Bioremediation has demonstrated authenticity and effectiveness because of its environmentally friendly elements. It can either be completed ex situ or in situ, contingent upon a few variables (Azubuike et al. 2016). Bioremediation is the utilization of microorganisms for the expulsion or degradation of impurities. The microbial cycles engaged with bioremediation are typically regular parts of variation, adaptation, or respiration that are frequently a part of carbon cycling or metal redox cycling. Hence, bioremediation regularly happens without direct intercession; nonetheless, bioaugmentation and biostimulation are frequently significant for the total evacuation of impurities within a prudent period (Krzmarzick et al. 2018).

Heavy metal bioremediation utilizing various microorganisms has been broadly applied as options in contrast to conventional techniques. Microalgae with extraordinary biological features such as high photosynthetic productivity can develop well under outrageous ecological conditions like higher salt contents, excessive temperature, heavy metals, and nutrient stress (Leong and Chang 2020).

**Biopesticides**

Biopesticides are derived from natural sources such as bacteria, animals, plants, and certain minerals; mainly used to depict a broad scope of formulated outcomes are to control pests, weeds, and diseases. As indicated by the US Environmental Protection Agency (EPA), biopesticides can be categorized under three principle classifications: firstly, plant-incorporated protectants (PIPs) or plant substances delivered by genetically engineered plants; secondly, microbial organisms and entomopathogenic nematodes the active ingredient; and third, pheromones (Morán-Diez and Glare 2016). Nonetheless, the absence of adequacy, conflicting field execution, and significant expense have commonly consigned them to niche items. As of late, mechanical advances and significant changes in the extreme climate have decidedly modified the standpoint for biopesticides (Glare et al. 2012).

**Biofertilizer**

Biofertilizers are living microorganisms that upgrade plant nourishment by preparing and expanding supplement accessibility in soils. Different microbial taxa, including beneficial microscopic organisms and parasites, are presently
utilized as biofertilizers. They effectively colonize the root inside, the rhizoplane, or rhizosphere. Azotobacters have been utilized as biofertilizers for over a century. It fixes nitrogen vigorously, elaborates plant chemicals, solubilizes phosphates, and stifies phytopathogens or lessens their pernicious impact. The use of wild sort Azotobacters brings about a better yield of cereals, oilseeds like sunflower and mustard, natural products like sugar cane and mango, fiber crops like cotton and jute, vegetable harvests, and the tree-like oak (Das 2019).

Hydrolysate can be utilized as a biofertilizer, protein supplements, domesticated animals feed, and bioactive peptides. It improves nutrients from the soil, C/N proportion, and water holding limit. The plant development advancing exercises of hydrolysate potentiate its possible use in natural cultivating and further develop microbiota and soil environment (Bhari et al. 2021).

Environmental monitoring

Environmental monitoring assumes a fundamental part in ecological security, particularly for managing and preserving natural assets. Environmental monitoring information usually is hard to oppose pernicious attacks since it is sent in an open and uncertain channel. With different environmental monitoring innovations, incredible leaps have been made in ecological assurance (Yang et al. 2021c). Biosensors and biomonitor systems are thoughtfully interrelated and strategically associated with a cooperative/synergistic scheme (CSS) to limit vulnerability, check expenses, and increment the dependability of contamination control. The CSS, in light of the mix of numerous data sources, can set up a local area network, consolidated into a wide area network, in this way offering the capability of better prescient capacity and more noteworthy lead-time cautioning at alert conditions than that given by separate, and independent surveillance modalities (Batzias and Siontorou 2007).

Chitosan coating technique

Chitosan coating can be helpful for coating fertilizers for slow and control release into the soil. This coating method reduces the redundant use of fertilizers and increases the scope of the crop needs. The coating of hydrolysate diammonium phosphates fertilizer by chitosan clay composites as an inner coating and paraffin wax as the outer coating has been proven effective by confirming the water holding capacity and phosphorous release easily in soil and water (El Assimi et al. 2020). Another usage of chitosan coating can also help extend the shelf-life of fresh-cut cucumber by coating it with edible chitosan solution of different concentrations. The performance observed reduced CO₂ production while packaged in air and nitrogen to maintain quality and improve retention (Olawuyi et al. 2019). Mushroom weight reduction, immovability, absolute phenolics, ascorbic corrosive, sensory quality, malondialdehyde, electrolyte spillage rate, and microbial were estimated. The outcomes show that treatment with chitosan-oil covering kept up with tissue solidity hindered increment of respiration rate and decreased microorganism counts, like molds, yeasts, and pseudomonad, contrasted with control treatment. The proficiency was superior to thyme oil treatment or chitosan coating (Jiang et al. 2012).

Bioenergy and biofuels

Among the renewable energy sources, biofuels can fill in as a superior choice to lessen the dependence on fossil fuels. Lignocellulosic biomass provides the most affordable biomass to produce biofuels. Bioethanol is one of the most generally consumed biofuels in the present world (Fatma et al. 2018).

Bioenergy is one of the numerous assorted assets accessible to fulfill our energy needs. It is environmentally friendly energy from late living natural materials known as biomass, generating products, heat, transportation fuels, and electricity. Supplanting regular biological systems with bioenergy crops across the planet will generally be unfavorable for biodiversity, with first-generation and high-yield crops having the most grounded adverse consequences. Meeting energy objectives with bioenergy utilizing existing negligible grounds or biomass extraction inside existing development landscapes might give more biodiversity-accommodating options than changing typical biological systems for biofuel generation (Núñez-Regueiro et al. 2021).

Biofuel is the primary product of bioenergy. Using it instead of diesel fuel will aid in reducing carbon monoxide and NOx particles. Ethanol is another bioproduct that aids in the conservation of natural resources. Biofuel is primarily focused on being created from raw resources that are not detrimental to the environment and result in pollution. Bioethanol produced positive results in reducing pollution. It is increasingly being used as diesel fuel for automobiles to keep the environment free of hazardous pollutants (Sarkar et al. 2021; Singh et al. 2022).

The use of natural resources in the manufacturing of diesel has resulted in price increases. The main concern is to shift focus to bioenergy to lower pollution levels in various parts of the world. New energy resources, such as wind, nuclear, and solar, have been employed to create energy-efficient fuel that can be easily recycled and reused (Arpia et al. 2021). Biofuel is the best form of energy because it is the cheapest to produce; it has proven to be a viable option for reducing or limiting the usage of nonrenewable natural resources. Biofuel has high efficiency and reduces the
number of dangerous pollutants released into the atmosphere. Edible and nonedible oils are used to produce biofuel. Furthermore, the transesterification process can be accelerated by using suitable homogeneous catalysts or nanoparticles (Sarkar et al. 2021; Singh et al. 2022; Verma et al. 2022).

**Sustainable chemical engineering**

**Basics of sustainability**

Sustainability can be defined as the measures taken by businesses against the health, safety, and environmental issues or HSE issues that can cause problems to the community surrounding it, such as stakeholders and contractors. The term sustainable development was first defined by the Brundtland Commission in 1987. They defined the term because sustainability refers to futurity (Basiago 1995). Thus, sustainable development is defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. A sustainable environment can be made when we keep up the efforts to maintain the requirements and social setting for the well-being of human health and the environment without overusing the ecological materials that help maintain sustainability. Thus, three criteria should be followed, also known as the triple bottom line. They are a successful business or enterprise, providing enough attention to maintain a healthy environment and continuing the efforts to keep up a sustainable environment (Das et al. 2018).

There are mainly two factors that can threaten sustainability: technology—when the rate of utilization becomes higher than the rate of production of resources by the environment, then the need of future generations is getting affected. Another factor is when the waste emitted by the technosphere affects the ecological sphere. Also, resource production is getting affected, thus, posing a threat to a sustainable environment (Das et al. 2018).

**Biomass-derived renewable carbonaceous materials**

Biological products made basically from carbon, hydrogen, and oxygen are called biomass. Biomass often pertains to plant or plant-derived materials such as lignocellulosic residues or biomass.

**Supported nanoparticles on nanocellulose**

Cellulose nanocrystals have applications such as paper, aero, hydrogels, and chiral materials (Khan et al. 2015). They are also used to support Pd, Au, and Ag nanoparticles catalysis. Moores and colleagues were the first to describe their application in enantiocatalysis (Kaushik et al. 2015). Through homogeneous organocatalysis, cellulose can be used as a chiral inducer. As an example of support of nanoparticles, Moores and colleagues have shown that CNCs help produce Ag nanoparticles from heavy Ag metals at room temperature by providing a high surface area. They also act as a reducer to allow the formation of Ag nanoparticles on biopolymer (Kaushik et al. 2016). The reducing activity of CNCs is due to several hydroxyl groups on their surface. This allows preventing the use of reducing agents. The suspension of two-phased or biphasic nanocellulose forms an ionic liquid-like system for the metal. It makes it easier for reactions involving ligand exchange. Another important application of these nanocomposites is photocatalysis, through which they allow the breakdown of dyes in an aqueous environment. This breakdown can be further enhanced by using nitrogen with the catalysts (Johnson et al. 2011; Varma 2019).

**Enzyme immobilization on nanocellulose**

The two ideal criteria to immobilize enzymes are low toxicity and biocompatibility. For example, heme proteins such as horseradish peroxidase have been fixed on AuNP bacterial CNFs (Zhang et al. 2010). Similarly, enzymes such as cyclodextrin glycrralsyltransferase and alcohol oxidase were fixed on CNCs containing Au, showing catalytic activity and high stability. Biosensors made in such ways (thiol sensors) are used in disease diagnosis (Schlesinger et al. 2015) (Varma 2019).

An eco-friendlier approach to making cellulose-based material is a citric acid and cysteine treatment (Chen et al. 2017). The products thus formed exhibits properties such as UV absorption, sensing of chemicals, and fluorescence. The principal characteristic of this mode of preparation is using water as the sole solvent in the reaction, thereby preventing pollution. One example of a product thus made is a durable hydrophobic paper with many functions (Baidya et al. 2017; Varma 2019).

**Chitin and chitosan**

Following cellulose, chitin is the next most abundant polymer. Its structure is closely related to cellulose as it is an extended chain of β(1–4)-linked space 2-acetamido-2-deoxy-β-D-glucose. Chitosan is a deacetylated form of chitin (acetylation below 50%). The structure of chitosan consists of glucose amine and acetyl glucose amine units. The most important feature of chitin is that it can be used as a catalyst without undergoing any changes. Chitin and chitosan have several characteristics that allow them to be used in various areas such as the cosmetic industry and medical fields. Their features include hydrophilicity, biocompatibility,
enhancement of wound healing, and more. Another notable feature of chitosan is producing nanoparticles that can regrow broken tissues (Varma 2019).

Chitosan has shown many catalytic applications such as Husigen cycloaddition (Chtchigrovsky et al. 2009), Michael addition (Khalil et al. 2010), and Suzuki cross-coupling (Martina et al. 2011). The characteristic feature of such strategies is the prevention of using organic solvents, thus making it more environment friendly. Such green approaches have been used to produce α-amino nitriles and imines where chitosan has been used (Dekamin et al. 2013; Varma 2019).

Microbeads are particles used in food, cosmetics, the medical industry, and more (King et al. 2017). Since these are made from polyethylene and polypropylene, they accumulate microplastics in the water bodies (Cole et al. 2011). As an alternative to this problem, Rogers and colleagues created chitin microbeads (Varma 2019).

**Interactions of pollutants in the environment through separation processes**

Pollutants release toxic substances that are not easy to separate into a single process. The solution to environmental pollution is detoxification methods and resource management. GT is a novel and efficient method to detoxify water using biomaterials such as a hybrid photocatalyst (Fu et al. 2021a, b).

**Bio-inspired hybrid photocatalysts for environmental detoxification**

Bioinspired hybrid photocatalyst contains microbial and biological adsorption coupling and photocatalytic treatment. They can be synthesized by combined biological and microbial oxidation and photocatalysis. They can mineralize toxic organic pollutants. The biopolymer process is divided into depolymerization and mineralization (Kumar et al. 2020). Chitosan and phthalocyanine are the active biomaterials used to promote light absorption in the visible range-hybrid catalyst absorption, and TiO2 accepts electrons to produce superoxide radicals by generating photons. Photocatalyst functions better when supported on biomaterials with porosity, large surface area, and functionality.

Bismuth-based photocatalyst (visible light-responsive) is used in wastewater treatment because of its nontoxicity, low cost, modified morphology, optical, and chemical properties (Kumar et al. 2020). TiO2 is the best photocatalytic material; doped with heteroatoms forms. A hybrid structure with g-C3N4 acts as a good visible light active photocatalyst. S–Ag/TiO2@g-C3N4 is a hybrid catalyst that helps in triclosan (TS) detoxification and visible light degradation (Xie et al. 2019). In the presence of boron carbonditrade, polyaniline has several purposes, such as hydrogen generation detoxifying organic and inorganic pollutants by acting as a photocatalyst (Raghu et al. 2021). To mineralize sulfamethoxazole as a pollutant in the pharmaceutical water and degradation of visible light, detoxification of environment, to remove harmful pollutant hybrid Ag2S/Bi2S3/g-C3N4 is used (Kumar et al. 2020). N-p heterojunction Bi4O512/Fe3O4 is a visible-light photocatalyst with recyclable magnetic properties. Some hybrid photocatalysts based on semiconductors are Bi2O3/Fe3O4, Bi2S3/Fe3O4, BiOBr/BiOI/Fe3O4, and Bi2WO6/Fe3O4 (Chang et al. 2020). TePc/amorphous TiO2 works under visible irradiation (λ > 550 nm) as a photocatalyst. Deoxynivalenol is degraded in water using ZnO/graphene hybrid photocatalyst (Bai et al. 2017). MXene (new photocatalyst)-based biomaterials are used to produce hydrogen, oxidation of organic pollutants, and reduction of CO2 (Sharma et al. 2021). These new areas of research are insighted by researchers majorly in developing nations, which will be helpful in the detoxification process with improved effect and discovering a new photocatalyst in its hybrid form.

**Bio-inspired biomaterial**

Gelatin, natural gums, pectin, starch, cellulose, chitosan, acetate, alginate, natural, inorganic biomaterials, and polymeric bio-nanoparticles are involved in biopolymer-based bio-inspired-biomaterials. Sol–gel technique is the precursor’s condensation process where metal salts get adsorbed onto the polymer. Controlled hydrolysis, electrospinning, spin and atomic layer deposition, hot press technique, and nanoencapsulation are the techniques that are used for the synthesis of biopolymer-based bio-inspired biomaterials. They are used to remove antimicrobial agents, food packing materials, heavy metals, and organic pollutants. Future studies can be used in wide applications in anticancer activities and biomedical areas (Kumar et al. 2020).

**Segregation of hazardous pollutants**

Due to rapid industrialization and population growth, various synthetic materials like heavy metals, pesticides, insecticides, steroids, dyes, and other organic materials are added to the environment, contaminating it. This contamination leads to cause various fatal diseases like cancer in humans. The majority of contaminants are added in water streams, affecting the aquatic environment adversely. Because of this, the separation of hazardous pollutants from the environment and especially water bodies are significant.
Adsorption is a surface phase transfer process practiced widely among other wastewater disposal technologies that are easy to carry out, fast, safe, whereas it has economic, versatile, feasible, and sustainable characteristics (Qi et al. 2021; Rizvi et al. 2020). To eliminate contaminants from water, adsorbents are used widely (Feng et al. 2019). Adsorbents can be of various types, like chitosan-based adsorbents, carbon-based adsorbents, and bio-based hydrogels. Bio-based hydrogels can be further classified into representative and composite bio-based hydrogels.

**Chitosan-based adsorbents** After cellulose, chitin is the second-largest abundant material in the environment. Alkaline deacetylation treatment on chitin produces chitosan. The processing of seafood like shrimp, crab, lobster, and green algae generates environmental waste that can be utilized to produce chitosan, making it a sustainable product. Chitosan is a natural linear polysaccharide that is polycationic with several primary amines and carboxylic groups on its surface, giving rise to many binding sites that entangle organic pollutants and heavy metals chelating and electrostatic effects (Feng et al. 2019). It degrades very slowly in the environment, making it suitable for its use for a long duration. Biocompatibility, nontoxicity simple modification, biodegradability, and cheap production are the properties of chitosan (Ali et al. 2021; Eltaweil et al. 2021). It is widely used in eliminating phosphates and nitrates, which cause (eutrophication and methemoglobinemia diseases) detrimental problems in the aquatic system (Eltaweil et al. 2021). Karthikeyan and Meenakshi (2021) showed that when chitosan was encapsulated with magnetic kaolin beads to get rid of phosphate and nitrate ions was found to work 8 times more efficiently in aqueous solutions. Various contaminants in water bodies like heavy metals, organic materials, phenols, dyes, and more should be separated by adsorbing on the adsorbent materials (Table 2) (da Silva Alves et al. 2021).

**Carbon-based adsorbents** Carbon-based adsorbents possess more excellent adsorption characteristics than cationic cellulose, and their adsorption mechanism is complex. Carbon spheres (CS) or carbon nanotubes (CNT) interact by electrostatic and hydrophobic interactions with contaminants present in the environment. They increase the surface area of the adsorbents (da Silva Alves et al. 2021). The oldest used carbon-based adsorbent is charcoal. It is used widely due to its large surface area, nontoxicity, and porosity to scale up. It helps eliminate inorganic heavy metal ions and organic textile dyes, pesticides, pharmaceutical products, and aromatic and phenolic compounds from contaminated water. Catalytic activation of pyrolyzed char produces carbon-activated adsorbent by using agricultural waste such as wood, coconut shells, wood, rice hulls, and industrial waste such as coke sawdust. The upcoming research needs to be done on recently developed carbon-based nano/micromotors, which requires more investigative aspects (Table 3) (Gusain et al. 2020).

**Representative biobased hydrogels** Hydrogel is one type of three-dimensional nano-adsorbent prepared by the sol–gel technique. They can be prepared by polymerization and monomers cross-linking (one-step process) and polymer synthesis (multiple-step process). During preparation, it is swollen by water with a network of cross-linked polymers; they do not dissolve in water but keep hold onto a few-fraction of water in its structure (Gulrez 2013; Gusain et al. 2020). Hydrogels characteristics are abundant with hydroxyl amide and carboxyl groups, economical and high porosity. They interact with pollutants using electrostatic interaction (Gusain et al. 2020).

The microporous chitosan is produced when genipin is cross-linked with hydrogel and incorporated nGO. Facilitation of cross-linking reaction increased robust 3D cross-linked networks exhibited by the increased storage modulus and swelling ratio. Hydrogels act as an effective adsorbent in diclofenac sodium (DCF), which is anti-inflammatory. CS/

### Table 2 The membranes used to remove the heavy metals and other pollutants from the contaminated water

| Source                  | To remove                      | Membrane                                | Reference                                |
|-------------------------|--------------------------------|-----------------------------------------|------------------------------------------|
| Aqueous solution        | Mercury                        | Natural and cross-linked chitosan        | Vieira et al. (2007)                     |
| Water                   | Cd (II) and Cr (III) ions      | ZnAl₂O₅·TiO₂ UF membranes               | Saffaj et al. (2004)                     |
| Wastewater from industries | Cu²⁺, Ni²⁺, and Cr⁶⁺         | Anion exchange polymer                  | Padmavathi et al. (2014)                 |
| Aqueous solution        | Phosphate                      | Polyethylene graft copolymers           | Senna et al. (2013)                      |
| Drinking and industrial water | Pb²⁺, Cu²⁺, and Cd²⁺ | Silica and cellulose-based MF           | Ritchie et al. (1999)                    |
| Wastewater              | Cd²⁺                           | Chitosan/γ-cyclodextrin                 | Muthulakshmi and Anuradha (2015)        |
| Water                   | Cu²⁺                           | CH/nylon-based                          | He et al. (2008)                         |
| Arsenate contaminated water | Arsenate                | Zr-based nanoparticle PSF HF            | He et al. (2014)                         |
| Irrigation wastewater   | Cd²⁺, Pb²⁺                     | Polyethyleneimine-grafted gelatin sponge| Li et al. (2016)                         |
| Carbon-based adsorbents | Source | Characteristics | Applications | Future notes | References |
|-------------------------|--------|-----------------|--------------|--------------|------------|
| Zero-dimensional carbon-based nanomaterials (OD-CNMs) | Carbon dots, carbon quantum dots (CDs), fullerene, carbon dots, nano-diamonds (NDs) | Surface functionalization, large surface area, optical aspects, minimum toxicity | Helps in improving absorption by eliminating pollutants and helps in photocatalysis | OD-CNMs composite needs to be prepared for the removal of toxic pollutants. OD-CNMs need to study further in detail | (Gusain et al. 2020) |
| One-dimensional carbon-based nanomaterials (1D CNMs) | Carbon nanotube (CNTs); (produced by chemical vapor deposition method) Carbon nanofibers (CNFs) (produced by electrospinning process) | Large surface area, different adsorption sites, porous nature, raised electrical conductivity, mechanical strength, raised aspect ratio, chemical resistance | Helps in eliminating inorganic (heavy metal ions and radioactive components); organic (dyestuff, pharmaceuticals, and other aromatic pollutants) | Since the adsorption is minimum, different heterostructures, porosity aspects of efficient adsorbents need to be studied | |
| Two-dimensional carbon-based nanomaterials (2DCNMs) | Graphene, graphene oxide, g-C3N3, graphene nanoplatelet, reduced graphene oxide, graphene, sheet-like nanoporous materials | Large surface area, optical transmittance, chemical and physical characteristics, great mechanical strength, raised electrical and thermal conductivities, chemical inertness, multifunctionalities, high current density | To remove different pollutants, mainly removal of organic pollutants | Magnetic composite, recycling, and regeneration approach. To try for fast removal g-C3N4 might extensively be used as an adsorbent. CNMs might replace other carbon-based adsorbents since they can remove all water pollutants. Adsorbents need to be produced on a large scale | (Gusain et al. 2020) |
| Multifunctional three-dimensional carbon | Hydrogels, fibers, aerogels, foam, sponges | 3D network, large surface area (versatile), highly flexible, thermally, mechanically, and chemically stable, raised surface hydrophobicity with oleophilic property, low densities, controlled morphologies | It effectively removes metals, dyes, oils, hydrocarbons, and organic solvents from contaminated water | When used with others such as hexagonal boron nitride, g-C3N4, MXenes, phosphorene, chalcogenides such as MoS2, WS2, etc. Studies in improving the adsorbent need to be done | |
Biosorption techniques

The biosorption strategy is achieved by cheap regeneration of biosorbent and recovery of sorbate. Biosorption is the physiochemical process in which the liquid phase (solvent) and solid phase (biosorbent) are involved in separating dissolved species by adsorption, precipitation, absorption, ion exchange, and surface complexation method. Biosorption is mainly used to eliminate heavy metals and is considered 1/10 times cheaper than the ion-exchange process. The merits of the biosorption strategy to get rid of pollutants are cost efficiency, process selectiveness, easy regeneration of biosorbent, no sludge formation, easy recovery of metals, efficient performance, feasible operational conditions, no additional nutrients required, inexpensive technology, and flexibility of operation is used to remove many pollutants (Senthil Kumar and Grace Pavithra 2018). The use of both living and dead biomasses of bacteria, fungi, and algae is beneficial for biosorption. Agro-waste materials are also used as biosorbents because of their excellent surface characteristics, widespread availability, and low cost. By altering the surface qualities of biosorberts, several physical and chemical treatments improve their biosorption capacities (Saravanan et al. 2021).

Advanced oxidation processes (AOP)

The AOP is a chemical technique for removing organic pollutants such as dyes, antibiotics, and other toxic pollutants from the wastewater. The H₂O₂, superoxide, and hydroxyl group radicals will help oxidize the toxic pollutants to less toxic or nonhazardous substances like CO₂, H₂O, and mineral acids (Theerthagiri et al. 2021). Many processes can be used here—Ozonation, photocatalysis, sonolysis, photolysis,
Fenton reaction, electrochemical reactions, and more. These help in the efficient removal of organic pollutants, but it has certain limitations in developing the semiconductor catalysts and lengthy procedures, especially in the case of photocatalysis. Many 2D semiconductor materials are of great interest to scientists. They play a significant role in efficient bioremediation and have exceptional properties. The materials include graphene, graphitic carbon nitride (g-C\textsubscript{3}N\textsubscript{4}), transition metal chalcogenides, carbides, phosphines, and metal oxides such as TiO\textsubscript{2}, ZnO, composites, and metal–organic frameworks (MOFs). Some of their properties include a large surface area, high conductivity, excellent mechanical properties, which help make the material surface more durable and stable and reduce electron and photon recombination, thereby helping ineffective separation of the free radicals (Theerthagiri et al. 2021).

The best practical method of removing toxic organic products, like azo dyes chemical solvents (Azimi et al. 2021), is by using sonophotocatalysis. This is a hybrid of 2 AOPs, i.e., sonolysis and photocatalysis. This combination can efficiently degrade these pollutants using ultrasound waves to produce cavity bubbles, activate the semiconductor material catalysts, and remove the toxic contaminants. These waves of about 20 kHz to 2 MHz led to cavitation. They helped continuously clean the material surface and helped to degrade both hydrophobic and hydrophilic organic pollutants. This is one of the very effective techniques in reusing the process repetitively with less maintenance and help in wastewater treatments (Theerthagiri et al. 2021).

**Cellulose and nanocellulose**

Cellulose is a polysaccharide of $\beta(1 \rightarrow 4)$ glycosidic linkages of $\beta$ D-glucose units and is found naturally in the cell wall of plants. Cellulose is high environmental-friendly material; there is wide availability, low cost, biodegradable, and renewable (Tu et al. 2021; Yang et al. 2021b). They are a perfect substitute for petroleum-synthesized plastics and can replace plastics in the long run since there is already an industry present and matured over the past 100 years and currently used to produce viscose, cuprammonium rayon, and more, which make use of certain toxic chemicals for its effective use (Tu et al. 2021). However, these chemicals can be replaced by specific cellulose properties and fiber structures. Yang et al. explained this with the concept of how tall trees stay upright. The wood from within consists of cellulose elementary fibrils or microfibrils, which strongly reinforce the cellulose nanofibrils to keep the upright structure of the tree and prevent it from falling. Cellulose nanofibers are formed by highly crystalline nanoscale fibrils (nanofibrils) and combine to form cellulose nanocrystals. These have a high aspect ratio and are flexible (Yang et al. 2021b). These nanocellulose materials are seven times stronger but five times lighter than steel. The hydroxyl grouping on the surface of cellulose can help combine with hydrogen bonding to form much nanocellulosic material interaction and increase the material performance and durability. Based on the number of hydroxyl groups on the surface, the mechanical and physical properties must be changed via many surfaces and intersurface engineering methods, both chemical and nonchemical. This can lead to novel functionalities and have various practical applications in structural, optical/electronic, phototonic, textiles, energy storage, and medical applications (Tu et al. 2021; Yang et al. 2021b). Studies are also being conducted to develop green cellulose solvents and regenerated cellulose materials of high strength through the bottom-up route (Tu et al. 2021). Nanocellulose-based aerogels form porous templates and are suitable for packaging applications instead of polystyrene-based packaging foams. They also have good water absorption, selective separation ability, CO\textsubscript{2} capture, and conductivity. Another one is nanocellulose films, which have very high water vapor absorption capacity and low oxygen permeability and can be used instead of plastic cling wraps for day-to-day food packaging. It also has good filtration technology and can be used in water filtration tanks and wastewater treatment plants (Table 4) (Nelson et al. 2016).

**Lithium-ion batteries (LIBs) and sodium-ion batteries (SIBs)**

Electronic battery waste has been a significant cause of environmental concern since there are few effective ways of recycling waste. However, scientists have developed ways to prepare advanced materials from these electronic remains like toner waste-specific metal remains, so on, that can be recycled and used as the anode material for lithium and sodium-ion batteries, instead of preparing new ones, which may not be environmental-friendly and nonrecyclable.

Li-CO\textsubscript{2} batteries (LIBs) came into existence after agreements and protocols like the Kyoto Protocol, the United Nations SDGs, and the Paris Agreement. This led to many countries finding alternative ways to curb CO\textsubscript{2} emissions and create a more carbon-low or carbon–neutral society. These clean storage technologies help electric power sectors decarbonize along with GT like electric vehicles (EVs) and energy storage systems (Tabelin et al. 2021). Compared to other rechargeable batteries, LIBs store more energy per unit mass. Lithium is known as white gold. It has varied applications from the manufacturing industry like lubricants, polymers, rechargeable batteries, and medicine to treat mental disorders (Tabelin et al. 2021). LIBs were costly earlier but are now made by lithium-intercalation using graphite anodes. Another novel energy storage GT is possible using Lithium secondary batteries (LSB), which uses green batteries derived from biomass like renewable
| SNO | Material     | Source                                                                 | Utilized in                                                                 | Pros                                                                 | Cons                                                                 | Recycling capacity | References            |
|-----|--------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|--------------------|-----------------------|
| 1   | Nanocellulose (NC) | Made from cellulose, the most abundant natural polymer from wood. The cellulose nanofibrils (CNF) and their cellulose nanocrystals (CNC) | Nanocelluloses mixed with other natural biomaterials like cellulose, starch, and alginate produce hydrogels, aerogels, mats, films, and bioplastics | Renewable, biodegradable, eco-friendly, carbon neutral, lightweight, and robust | Still requires some chemical solvents to prepare cellulose materials before binding. Research ongoing for green solvents | Highly recyclable   | (Yang et al. 2021b)   |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Tu et al. 2021)     |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Wang et al. 2021b)  |
| 2   | Ferric oxide | Produced from heated toner powder in exhausted printer cartridges     | Anode material in sodium-ion batteries                                       | Renewable, low cost, and good electrochemical performance as an anode in a sodium-ion battery | Structural volatility and low Coulomb efficiency. Carbon combined with Fe$_3$O$_4$ gives a stable electrode material | Recyclable         | (Arjunan et al. 2021) |
| 3   | Graphite     | Not specified                                                          | Anode material in lithium-ion batteries                                      | High Coulombic efficiency and long cycle life                         | Not a suitable anode material in sodium-ion batteries and SIHCs. Requires tin (Sn) to form a composite | Is recyclable       | (Tabelin et al. 2021) |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Palaniselvam et al. 2021) |
| 4   | Starch       | A polysaccharide is used to store energy in plants. Obtained from potato, rice, corn, wheat, and cassava | Biodegradable packing film made of cornstarch-chitosan pluronic F127, bio-painting papers, corn, and arrowroot with NaClO$_3$ and glutaraldehyde act as flexible, transparent, and highly conductive electrolyte membranes. Used in drug delivery systems | Highly abundant in nature, low cost, high biocompatibility, and biodegradability | Poor mechanical properties and water resistance                      | Is recyclable       | (Fonseca-García et al. 2021) |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Kou et al. 2021)    |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Cao et al. 2021)    |
| 5   | Chitosan     | Natural linear amino polysaccharide. Polymer extracted from shells of shrimps crabs | Used in biodegradable packing film made of cornstarch-chitosan pluronic F127, Improves the stability of drugs and can be used as a nano-drug carrier | Biocompatibility, antimicrobial, antioxidant increase wound healing process, are nontoxic, and have a low oxygen permeability | The extraction process of chitosan differs from the source. There is no standard procedure for all types of sources | Is recyclable       | (Fonseca-García et al. 2021) |
|     |              |                                                                        |                                                                             |                                                                      |                                                                      |                    | (Kou et al. 2021)    |
| 6   | Flavonoids   | The biggest group of polyphenols has 8000 compounds. Consists of flavones, flavanols, iso-flavonoids, etc | Na-alginate NPs doped with pinostrobin—as an anticancer drug, biopolymer films with propolis—active packaging material and cleaning agents | Natural antioxidant compounds create a biological protective barrier and have biocidal properties against microorganisms | Not specified                                                    | Not specified       | (Pawlowska and Stepczyńska 2021) |
| SNO | Material | Source | Utilized in | Pros | Cons | Recycling capacity | References |
|-----|----------|--------|-------------|------|------|-------------------|------------|
| 7   | Transition metal chalco- genides (TMDs) | Chemical compounds consist of at least one chalcogen anion (sulfur or selenide) and electropositive transition metal element | Sonophotocatalysis, visible light-harvesting applications | Remarkable and unique characteristics compared to bulk parent compounds and highly covalent species | Photocorrosion. To prevent this, TMDs are doped with cocatalysts like Ni$_{x}$Mg$_{4-x}$S$_4$ MXene sonophotocatalyst | Not specified | (Theerthagiri et al. 2021) |
| 8   | Hard carbon | Not specified | Anode material in sodium-ion batteries | High Na-ion storage capacity, appropriate working potential, excellent cycling stability, and natural abundance | Not many studies have been conducted to understand the interactions between sodium and hard carbon during the electrochemical process | Highly recyclable | (Wang et al. 2021c) |
| 9   | Biochar | Produced by pyrolysis under anaerobic conditions | To improve soil fertility, carbon sequestration captures CO$_2$ from the atmosphere in healthcare as filler media and drug-delivery agents | Has wide applications in effective regulation of climate change, very useful in agriculture, renewable batteries, and healthcare | Unable to reduce N$_2$O levels, compared to charcoal | Not specified | (Ok et al. 2015) |
| 10  | Polylactic Acid | Produced by polymerization of lactic acid, obtained from fermented starch of corn and rice. Also obtained from waste material such as cellulose, kitchen garden, or fish | Can act as nanocarriers for drugs used in prosthetics, orthopedics, face masks, cosmetic industries, textiles, and bioremediation | Biodegradable polyester with good compatibility, good processability, and mechanical properties | Not specified | Not specified | (Pawłowska and Stepczyńska 2021) (Kou et al. 2021) |
| 11  | Polyhydroxybutyrate (PHB) | Produced by microalgae and various bacteria under particular carbon excess stress conditions | Wound dressings, microspheres used in drug delivery systems, tissue engineering, as an antiadhesive agent against shellfish pathogens, bio-additives in paints, and used in the food packing industry | High biodegradability, high biocompatibility, nontoxic, and creates no environmental pollution | Cultivation and harvesting of these microorganisms are limited due to the expensive equipment used in the process | Not specified | (Pawłowska and Stepczyńska 2021) |
| SNO | Material            | Source                                                                 | Utilized in                                                                 | Pros                                              | Cons                                      | Recycling capacity | References                  |
|-----|---------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------|-------------------------------------------|-------------------|----------------------------|
| 12  | Lignin              | 2nd abundant component is wood. It is an amorphous, 3D oxygenated p-propyl phenol polymer. Industrially obtained as a byproduct of cellulose-rich pulp fibers | To produce different synthetic polymers with physicochemical properties. Some commercial products include Kraft lignin, soda lignin, organosolv lignin, and lignosulfonate | High hydrophobicity, antioxidant, antimicrobial, UV absorption, thermal stability, and rigidity | Not that good and active to be utilized as an adsorbent and surfactant. Requires further processing to lignin nanomaterials to have this property | It can be recyclable | (Wang et al. 2021b)         |
|      |                     |                                                                        |                                                                            |                                                  |                                                                         |                   | (Kou et al. 2021)         |
| 13  | Dioscorea hispida tubers | Produces starches and fibers. It is a poisonous tuber plant that contains the alkaloid of Dioscorides | Its waste can be alternative biomass. It has excellent potential to be used as renewable filler material for food packaging applications and as a crude drug for inflammation | Can generate large quantities of sustainable lignocellulosic materials every year and produce starch, bioplastics that are eco-friendly and highly renewable | The tubers have to be immersed in distilled water for 5 days in order to remove/fully detoxify the Dioscorides | Is recyclable      | (Hazrati et al. 2021)       |
| 14  | NC-based aerogels    | Low-density solid materials, made up of CNFs of nanocellulose and chitin nanocrystals | Water treatment, controlled drug delivery, and dye adsorption              | Antioxidant, antimicrobial, etc                  | Not specified                                                            | Is recyclable     | (Yang et al. 2021b)         |
|      |                     |                                                                        |                                                                            |                                                  |                                                                         |                   | (Nelson et al. 2016)      |
organic biomolecules and inorganic carbon molecules (Jin et al. 2021).

Sodium-ion batteries (SIBs) were introduced after Li-ion batteries in the commercialized market at the end of the twentieth century (Wang et al. 2021c). However, they were not studied in that much detail compared to Li-ion batteries. However, scientists are now looking for an appropriate anode material and find hard carbon (HC) to be a promising material since it has an excellent sodium-storage capacity, good recycling stability, and is a naturally available material (Wang et al. 2021c). With such anode materials, Na-ion batteries (SIBs) can slowly be used as an alternative to lithium-ion batteries despite having less energy than LIBs but a safer and better battery than lead-acid batteries (Palaniselvam et al. 2021).

**Biodegradable materials**

Nonbiodegradable plastic waste has become a significant pollutant in our water bodies like the rivers and seas. About 8 million tonnes of plastic waste is dumped each year. If this discharge pattern continues, we will have more plastic than fish by 2050 (Tu et al. 2021). Scientists have entirely focused on the use of biodegradable materials like starch, cellulose, chitosan, biomass, resins, gums, jute, gelatin, pectin, waxes, and inorganic compounds like TiO₂, ZnO, chalcogenides, and ways to incorporate eco-friendly and sustainable habits from using jute or cloth bags for daily grocery shopping to high-production packaging using biodegradable films made of cornstarch and chitosan in industries. Electronic devices made of renewable or biodegradable materials that disintegrate into harmless by-products are becoming increasingly popular. Low-energy, low-cost procedures including low/nontoxic functional materials or solvents are required to construct such “green” electronic devices on an industrial scale (Li et al. 2020).

Biodegradable films made of cornstarch and chitosan with poloxamer F127 are very durable films with good moisture barrier properties. They are suitable for packaging food and medicines (Fonseca-García et al. 2021). This shows the ability of starch and chitosan to be used as significant polymers that can be modified into thermoplastics mixed with synthetic polymers. It is environmentally friendly, nontoxic, and easily decomposable (Fonseca-García et al. 2021). *Dioscorea hispida* tubers also have an excellent potential to be used as a renewable filler material for food packaging films (Hazrati et al. 2021). A second application can be made natural antibiotics using natural modifiers like polyphenols, biocidal additives like sodium alginate nanoparticles doped with pinostrobin and used as an anticancer drug. Naringenin has antioxidant and anti-inflammatory properties against the SARS-CoV-2 virus (Pawłowska and Stepczyńska 2021). Biodegradable materials such as Nanocarriers can help in the effective encapsulation of the active pharmaceutical ingredient (API) for essential drugs, nutritional capsules, and supplements.

New natural biopolymer combinations can be degraded into harmless compounds that are nontoxic and enhance biocompatibility, have high loading efficiency, and are safe to consume (Kou et al. 2021). These nanoparticles drug delivery systems can be highly effective for tumor-targeted therapy (Kou et al. 2021). Biochar is another biodegradable material made of solid carbon through pyrolysis of biomass. Biochar can be used for drug delivery and detoxification for patients suffering from poisoning or drug overdose (Ok et al. 2015). In terms of waste management, many natural filler materials can be utilized. *Dioscorea hispida* tubers waste can be used as a waste-filler material and an alternative biomass source (Hazrati et al. 2021). Biodegradable materials also have agricultural applications. This includes promoting crops’ growth by using cornstarch gelatin composites and modified tapioca coated over controlled-release urea particles to enhance the nitrogen-producing capacity of plants (Cao et al. 2021). Biochar is used in plants to help fix the CO₂ from the atmosphere in a stable form and prevent climate change conditions (Ok et al. 2015). In electronic technology, starch-based coatings can enhance the electrochemical performance of batteries. Also, starch content from arrowroot and corn can be combined with chemicals like sodium perchlorate (NaClO₄) and glutaraldehyde to produce highly conductive electrolyte membranes (Cao et al. 2021). Lastly, biochar can be used as suitable supercapacitors. Biochar coated with graphene can act as good anode materials for batteries (Ok et al. 2015).

**Process system engineering and IR 4.0**

**Industry 4.0**

The Fourth Industrial Revolution, also known as Industry 4.0, envisions a rapid change in technology, industries, societal patterns, and processes due to increased interconnectedness and smart technologies. It was introduced by Klaus Schwab, the founder and executive chairman of the World Economic Forum, to highlight that the changes being experienced are more than just efficiency gains but rather a drastic shift in industrial capitalism. Humanity is currently confronted with two significant challenges. One of them is achieving the SDGs, while the other is adapting to the changes that marked IR 4.0.

Industry 4.0 was initially announced in Germany in 2011 at the “Hannover Fair” event as a proposal to form a new concept of German economy policy based on high technology initiatives, marketing the start of the IR 4.0. The rapid evolution of technology allows for a thorough examination
of its impacts on the economy, society, and environment. There has been a dispute between the ideals of industrial production, economical expression, and environmental sustainability over the decades. Aside from water and energy usage, the extraction of raw materials and soil exploration has resulted in massive waste production.

Industry 4.0 is a novel engineering paradigm characterized by high productivity, procedural efficiency, and environmental sustainability. This new sector is seen as a paradigm for manufacturing that is sustainable. And one of the elements that most underwrites this information is the vast collection of primarily revolutionary technologies in Industry 4.0 (Bortolini et al. 2017). Mainly because such technologies are not necessarily unheard of, what changes is the interaction between them in the context of Industry 4.0. This work aims to demonstrate the full potential of Industry 4.0’s leading technologies for their very effective eco-friendly management. Thus, it is feasible to grasp how integrated technologies collaborate for an environmentally sound and sustainable positioning of Industry 4.0 in all sectors (Aceto et al. 2020). Industry 4.0 makes better use of natural resources, produces less waste, has leaner processes, and has more extended machine and equipment life cycles and technological advancements (Jiang et al. 2021).

**Futural skill requirements** As Industry 4.0 adopts an enhanced ecologically sustainable conscience and implements its potential technologies, the procurement of energy resources and all power generation is done depending on the requirements and demand, without exaggeration. Consequently, even as a precise amount of a resource to be used in production is acquired, expenditure on the purchase of productive inputs tends to decline or be under control. Sustainable environmental behavior in Industry 4.0 can increase revenue while cutting costs and expenses. Similarly, across Industry 4.0, the usage of machinery and equipment may be shared. This comprises industries sharing their operational capacity and is a means for them to provide services. The supplying industry may keep its machinery running and generate variable income even when it is not functioning in the industry from which it runs. At the same time, the machinery-using industry continues to operate without hindrance or loss of demand.

This industrialization strategy is distinct in employing several technologies to achieve more environmentally consistent and efficient industrial production. Such technologies, when used efficiently, may make a substantial contribution to environmental sustainability.

**Blockchain technology**

Blockchain is a distributed database of completed activities and digital events shared among participating parties. A network participant agrees on, mathematically links, and stores each transaction, ensuring its immutability. Blockchain enables us to manage our digital operations and interactions far more securely and dependable (Lage 2019). The dependability given by blockchain will witness a significant alteration of industrial processes in the next years, enhancing synchronization between different agents in the value chain and excessive automation of decision-making. It is also expected to transform its business models in the future, like how the Internet, the most significant technological innovation in history, revolutionized the world (Esmaeilian et al. 2020).

**Blockchain technology and green IoT** The vast expansion in global industrial activity over the last several decades has resulted in a considerable increase in the consumption of fossil fuel energy resources, while technological advancement has amplified the carbon footprint and hence global warming. The enormous rise in energy usage brought on by IoT technology has posed a new issue and shifted our attention to developing a more environmentally friendly IoT ecosystem (Sharma et al. 2020). The Green Internet of Things (GIoT) is a new topic that has piqued the interest of researchers and businesses since it offers energy-efficient services and allows for the generation and use of renewable energy. Blockchain technology has emerged as a widely used IoT technology, receiving significant interest from energy corporations, start-ups, financial institutions, governments, and researchers. It is essential to clearly understand the role of developing blockchain technology in the GIoT ecosystem, which offers the critical aspects that must be considered to establish a GIoT ecosystem and examine how blockchain technology helps to green the IoT ecosystem (Polas et al. 2022; Sharma et al. 2020).

The term GIoT refers to a new generation of IoT design principles. The green smart device (GSD) is a fundamental unit of GIoT for energy conservation (Tan et al. 2021). It can prove fruitful to conserve energy, minimize emissions, reduce environmental pollution, and harm the human body and environment. In the GIoT, user access and management of GSDs have grown increasingly challenging due to the availability of a large number of heterogeneous bottom-layer GSDs. Users must use multiple GIoT apps and access different GIoT cloud platforms to access and control these heterogeneous GSDs since there is no uniform GSD management system. This disjointed GSD management paradigm complicates user access and control for varied GSDs and limits GSD application scalability (Tan et al. 2021; Zhu et al. 2015).

**The primary goals of the IR 4.0**

The Fourth Industrial Revolution’s primary goal is to increase revenues and elevate the standard of living. As a
result of modern technology, products and services have been produced that may help and support their professional and personal lives. Furthermore, because new technologies may readily intrude on people’s privacy, governments must build effective methods for monitoring and organizing technology platforms. The evolution of customized medicine, which will allow people to detect their propensity to particular diseases, is another important area addressed by Industry 4.0. New biomarker-based technologies are predicted to characterize practically all human metabolic activities. The scope and the profound impact of the changes imposed on production, management, and effective governance all contribute to Industry 4.0 as a new revolution and the speed with which technical-scientific breakthroughs are made and spread (Dogaru 2020).

**Renewable energy perspectives**

Renewable energy, often known as alternative energy, is derived from a natural source that does not diminish when utilized. It is a type of energy that has acquired popularity in the past few years. It does not harm environmental sustainability. One of the significant sources of pollution is a scientific and technical progress that is unrelated to proper pollution control methods. Scientific innovation for industrial development has triggered intense debates and concerns, particularly at the level of environmental regulations, while neglecting the maintenance of ecological integrity and resulting in significant adverse manifestations. The goal of eco-industrial development, which is closely linked to environmental sustainability, was to find a variety of answers to the complex challenges of renewable energy management and usage and the consequences of climate change. Renewable energy is the best and cheapest option as an alternative energy source. Renewable energy has enormous potential worldwide, particularly in India. The optimal use of renewable energy resources has the potential to reduce the global impact of climate change. Renewable energy is created primarily from virtually endless sources such as wind, solar, geothermal, tidal, biomass, and other renewable energy sources. As a result, boosting renewable energy sources could rescue our future from climate change and a sustainable food production standpoint (Kumar et al. 2021).

**Current Industry 4.0 research for encouraging the sustainability of supply chains**

Sustainable supply chain development emphasizes environmental and economic benefits, whereas Industry 4.0 development involves complete system integration and automation. Manufacturing equipment can become self-contained as part of Industry 4.0, allowing it to design, develop, and build items without human interaction. Industry 4.0 enables more product customization by increasing manufacturing flexibility. The machines will interact with one another to carry out the manufacturing plant. On the other hand, firms face plenty of challenges in implementing Industry 4.0 efforts, which could impact supply chain sustainability (Bányai and Akkad 2021).

Industry 4.0 ushers in a new era of supply chain transformation through digitalization and smart technologies. Industries worldwide achieve productivity by enabling technologies to avoid perishing in this unpredictable and ambiguous environment. Industry 4.0, on the other hand, has negative aspects that affect a company’s supply chain both before and after deployment. The major issues include employment loss, lack of Industry 4.0 knowledge among network suppliers, inadequate funding for technology advancement, and lack of IT security guidelines and policies that affect both customers and suppliers in the supply chain network. These challenges can heighten uncertainty and risk, potentially disrupting the supply chain.

**IoT-enabled energy management**

The IoT is a new technology that connects physical components over the Internet, including consumer electronics and industrial machinery. By utilizing appropriate sensors and communication networks, these devices can provide crucial data and enable users to obtain various services. One of the primary advantages of blockchain applicability to IoT is the decentralized architecture that blockchain can provide to IoT, especially to the industrial environment, which has more severe needs (Fig. 2) (Hossein Motlagh et al. 2020).

IoT also distinguishes itself by allowing individuals to be free of a particular location. As a result, the person may operate the tools without being in a specific area. The devices are in direct connection, and the person is one of the communication nodes, similar to other terminals. In this context, any item recognized on the Internet by an IP address is considered a linked thing. It also includes the hoops used by animals in breeding farms, natural reserves, oceans, and woodland areas.

IoT allows humans to control close-by or faraway devices successfully. For example, a user may manage and run his automobile engine from his wristwatch or handle his washing machine’s washing tasks. He can also remotely examine the contents of the refrigerator. Nonetheless, these are some examples of IoT in its most basic form. The mature version involves a direct connection between the machine and the machine. For instance, the refrigerator may interact with the shopping center to order and acquire goods without human participation. Moisture and heat sensors at the atmospheric...
monitoring station can trigger the discharge of a water evaporator. Many instances of IoT might be created that could become a reality in our everyday lives (Lage 2019).

Logistics and transportation in IR 4.0

Industry 4.0 is encouraging business model changes, resulting in the birth of new professions and the loss of certain lines of work that will be substituted by machine intelligence and gadgets. The beginning of Industry 4.0 is characterized as worldwide progress, which may require a longer time to accomplish. Skills, talents, and knowledge in the workforce have to be improved. When Industry 4.0 is fully implemented, computers will interact with one another and make choices without human intervention. Industry 4.0 technologies aid logistics by helping to optimize transit routes, maximize storage space, and plan (Holubčík et al. 2021).

The Port of Hamburg is one such example. Every year, 140 million tonnes of products are transshipped, with the quantity expected to treble by 2030. However, there is insufficient room in the port. As a result, the officials of the Port of Hamburg were faced with the task of assuring speedier container transshipment.

Global markets are changing as product life cycles are shortened, product complexities are increasing, and global supply networks are becoming more crucial. As a result, firms strive to be more adaptive, faster, less expensive, and more capable of responding to changing market conditions. For companies who want to address these issues adequately, Industry 4.0 is the approach (Jankalová and Jankal 2018).

Environmental/green economies

Having a sustainable, low-carbon, and green economy has become the need of the hour in recent times. Governments all over the world have now realized the existence of climate change and how greenhouse gases, CO₂ emissions, excess pollution of water bodies due to nonbiodegradability of plastic waste, use of excess chemicals and cheap synthetic solvents in fashion, textiles, automobiles, and sports industries for so-called “durable” products, increased number of animal species on the endangered list of extinction, forest fires of the Amazon, increased floods and other natural disasters, and many more instances have negatively impacted the environment as well as human lives. In addition to these, the COVID-19 pandemic has sent alarm rings to the world. During lockdown times, everyone realized how they had misused and exploited the free resources provided by the Earth for their greedy needs. This section will include an in-depth analysis of first, how the COVID-19 pandemic has shifted the paradigm of the world toward a green transition and how governments can make the necessary changes through deals, financial stimulus packages, and pricing the
carbon emission and externalities to bring sustainable solutions for a safe and greener economy. There are still many challenges in this area. There is a great need for research to develop reasonable and easy solutions. Second, how scientists and governments work together for green stimulus packages and how green production capabilities can be enhanced in industries. The last two parts discuss how sustainability can be incorporated by individuals, communities, governments, and the world to protect the environment. There is a need to spread awareness regarding the damage and destruction happening to our environment by human activities and protest about it and practically implement those policies set by the governments and companies. This can be done through sustainable transitions, ecological modernization, reconsidering the concept of growth, and how it can be made into sustainable growth. These practices, and at the same time continuous research and analysis, will help us to create a more environmental-friendly, safe, and sustainable world and the planet. GTI may indirectly impact carbon emission efficiency by affecting economic development and urbanization (Khattak and Ahmad 2021).

Green transition and COVID-19 post-pandemic research agenda

The COVID-19 pandemic has affected all spheres of life and has given the world economic, environmental, social, and political challenges (McNeely 2021). It was a devastating time for human existence, which significantly strained the health sector. Both government and private hospitals and the world witnessed significant changes and consequences on the environment, economies, and the energy sector (Priya et al. 2021). The SARS-CoV-2 virus originated in Wuhan, China, and was said to have zoonotic links (McNeely 2021; Priya et al. 2021). This disease was easily spread to the world via globalization trade and travel. Even the governments of the world were not able to handle it well. There was slow and poor preparedness to respond immediately (McNeely 2021). The world witnessed lockdowns, shutting down of air travel, fully online educational classes, and temporary closure of factories, offices, and industries to implement social distancing to reduce the transmission of the virus.

The unemployment rates were at an all-time high; reusable packet containers became hazardous waste due to use by COVID-positive patients; there was a huge increase in the amount of medical waste, including PPE kits, gloves, and masks. Moreover, due to increased online shopping and food deliveries, organic and inorganic domestic waste significantly increased (Irfan et al. 2021). There was a sense of forgetfulness to live a sustainable way of life with the arrival of the pandemic. In the USA, officials had to stop all recycling activities due to the fear of spreading the virus among the workers (Irfan et al. 2021). A significant change was observed during the lockdown time in the CO2 emission and GHG levels (Kumar et al. 2022). This made the governments and scientists realize how the closure of certain activities led the planet to heal itself and post-pandemic scenario, how the GHG and CO2 emissions can be controlled (Kumar et al. 2022). There was also a sharp reduction in water pollution, the surface, coastal, and groundwater quality significantly improved. However, excessive soil pollution occurred due to a huge increase in medical and household waste (Yang 2021a). Post-pandemic, practical action plans and policies need to be implemented to control these emissions sustainably through green economic activities (Irfan et al. 2021; Kumar et al. 2022). As per Irfan et al. (2021), the more we move toward a green economy, the better global sustainability can be achieved. The following parts will explain in detail the lessons learned from the lockdowns; the Green New Deal, which is being initiated; how the governments are providing green economic stimulus packages; and how to fix the prices for carbon emissions, using concepts of externality and if a common fixed price will be feasible for the world.

Lockdown lessons to diminish carbon emission

As the pandemic raged across the world, all movements were restricted to prevent the spread of COVID-19—from the ban on airline travel, closure of schools, offices, factories, industries to the complete stoppage of transportation of oil, gas, and other goods. The regular amount of pollution from transportation highly reduced the release of fumes from factories, powerplants, oil refineries, and coal mining resulted in reducing CO2, NO2, CH4, and other GHGs emissions (Kumar et al. 2022; McNeely 2021). During pre-pandemic days, industrialization and specific automobile industries, which mainly were utilizing fossil fuels for energy, resulted in an upsurge in GHG emissions. At least one-fifth of the CO2 emissions came from transportation, with 75% from road transport (Kumar et al. 2022). Moreover, this was significantly reduced during the lockdowns to a global 7.8% decline in CO2 emissions in 2020 compared to 2019 (Kumar et al. 2022). However, as per Irfan et al. (2021), this reduction in GHG emissions was not sustainable when considering the normal functioning of global businesses. Post-pandemic, there has to be a series of long-term mitigation strategies to maintain this reduced level of GHG emissions (Irfan et al. 2021). As per Kumar et al. (2022), in 2021, there can be a 6% upsurge in the GHG levels to stabilize the economy in the USA. There was also a decrease in GHG levels due to less aviation traffic, at least 40% less than the average in 2020 (Priya et al. 2021). The positive impact of COVID-19 was that CO, NO2, PM2.5, and PM10 were
reduced significantly in the atmosphere. In contrast, the SO₂ and O₃ levels were either constant or slightly increased in Lyon, Kolkata, Peru, and Spain (Yang et al. 2021a).

The Green New Deal

As per McNeely, the governments of all countries are adopting a Green New Deal, especially for renewable resources—wind, solar, and water. The aim is to reduce 80% of the energy dependency on fossil fuels by 2030 and undergo a complete transition of energy dependency on renewable resources by 2050 (McNeely 2021). This should be a joint effort by the governments, academic institutions, scientists, NGOs, healthcare workers, and the public. Scholars in environmental science must advise policymakers on formulating scientific methods, understanding the risks involved, and creating public awareness. This can result in inadequate policies that can help reduce GHG emissions (Irfan et al. 2021). The deal includes hydrogen economy—for low carbon energy systems because hydrogen can be utilized as an energy carrier with a similar role as carbon. Next is the transition to renewable energy through bioenergy with carbon capture (Kumar et al. 2022). Recycling institutions can significantly reduce the amount of waste discarded and reused again. Green innovation can be increased by creating electric vehicles. Also, green’s low-carbon circular economy can be created by using biodegradable, advanced materials (Priya et al. 2021). Energy efficiency (EE) investments are a good clean energy transition practiced by the European Union (EU) for green economic recovery. This can be done using innovative decision support (DS) tools and standardized methodology tools like the Triple-A Horizon. As per the International Energy Agency (IEA), this can help in boosting the economy by creating jobs, reducing air pollution and GHG emissions, low energy bills, and efficient energy systems. Governments worldwide can apply this in 3 essential sectors—infrastructure, construction of buildings, and technology replacement using GT (Fig. 3) (Karakosta et al. 2021).

Due to the pandemic, the EE investments were significantly reduced, especially in the oil sector. However, as the situation improves, these investments shall continue. The Green Deal also includes the “One Health” policy, which focuses on human, animal, economic, and environmental health and maintaining a good balance and improving the interaction between humans and animals by creating more dedicated areas for national parks and sanctuaries. The animals can live in their wild environments and support biodiversity. In agriculture, healthier approaches can be created to grow food in sustainable ways, for example, hydroponics and aquaponics. In the food industry, more investments are to be made in plant-based proteins and meats to reduce dependency on livestock and create healthier alternatives for a high-protein diet (McNeely 2021).

Government-financed stimuli

Governments worldwide have planned to develop a stimulus for maintaining a good balance between economic recovery and climate issues. A good example to explain this is upgrading the street lights in India with LED lights, which reduced the GHG levels by about 5 million tons in 9 years and created 13,000 jobs (Abhinandan Kumar et al. 2022). The governments can come up with bio-cities in the urban settlements where they can build GT and green material-based buildings (EE investments can be included), promote bio-based public transportation for traveling instead of using individual cars, and promote green spaces by growing trees and urban forestry to engage people in recreational activities and protecting nature around cities (Galanakis et al. 2022). Governments can provide transportation stimulus packages for sustainable mobility. These are low-carbon policies to reduce GHG levels due to vehicles, significantly individual cars (Griffiths et al. 2021). The concept of MaaS (mobility-as-a-service) can also be created—like public transport and Uber, where the public can book seats online and contribute to reducing CO₂ emissions (Kanda and Kivimaa 2020). The government can directly buy EVs for the public, which are contactless and can be used as taxis for the public, as delivery vehicles, and buses (Griffiths et al. 2021).

The countries should also focus on green housing to enhance sustainable living. The COVID-19 pandemic has led to the public spending more time at their homes—working and for leisure time. Residential complexes must be developed to improve indoor environment quality, using sustainable and durable materials using the green housing topic model (Kaklauskas et al. 2021). The United Nations have provided the SDGs to set specific policies to follow them and maintain the 3 pillars of sustainability—social, economic, and environmental sustainability, post COVID-19 pandemic (Ranjbari et al. 2021).

Pricing the carbon externality

The externality is a concept of economics that involves an industry or institution that is not charged or punished for the harm it provides to another, i.e., the environment. As far as industries are concerned, it is essential to keep a check on the CO₂ emissions released into the environment, having dangerous consequences. Hence, it is very crucial to charge them for this. This pricing can help them act on negative externalities carbon emissions and correct the spatial associations of environmental pollution (Shen et al. 2021). Carbon neutrality is another case where the externalities are
internalized to create a carbon-double input level to inno-
vate green technologies to produce low-carbon goods (Wang et al. 2021a, b, c). Generally, three policies would address climate change as an externality—command and control regulation, carbon taxes, and cap and trade (Mintz-Woo 2022). Both carbon taxes and cap and trade are quantitative instruments for carbon pricing. Suppose we increase the price of GHG emissions, in that case, the producers themselves will reduce their polluting activities and find alternate ways of disposal (Mintz-Woo 2022). In the USA, most of the earlier policies dealt with the cap-and-trade policies and carbon taxes, which considered GHG emissions an externality leading to climate change. However, it had been insufficient to significantly reduce the emission levels (Boyle et al. 2021). As per Mintz-Woo (2022), the USA prefers the command-and-control regulation since it either prohibits or sets specific limits regarding the emission levels. However, overall, carbon pricing is the most effective way to price the externalities. This is because carbon pricing is flexible, highly efficient, and comprehensive. Here, it rewards the companies who reduce their emissions, which can recycle their revenues (Mintz-Woo 2022). Carbon pricing can be done either through carbon taxes or cap and trade and could be a point of discussion.

**Green stimulus and production capabilities**

GT has become a significant factor in economic growth with sustainability. Various fields are now being utilized to reduce GHG emissions and hazardous waste production. This includes bio-based sustainability, green nanotechnology, green chemistry, green IT industry—cloud computing and data mining (Nazir 2021; Wang et al. 2021a). Many countries in Europe are coming up with an economic

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*Fig. 3* The Green New Deal, goals, and strategies for sustainable and eco-friendly transition. It includes bioenergy, biodefence, bio-cities, biodiversity, bioeconomy, green housing, agriculture, and bio-based materials.
stimulus that aims to produce in a climate-friendly manner and increase the sorting and recycling of basic materials like aluminum, cement, and plastic (Chiappinelli et al. 2021). The production of green electricity is possible by the government creating partnerships (public or private) to provide the necessary infrastructure using basic-recycled materials. By 2025, the aim is to get 20% of basic materials in recycled form in Europe via low-emission and recycling processes (Chiappinelli et al. 2021). In order to increase green consumption among the public, it is essential to develop green products like green detergents, ecological paper products, energy-saving laptops and mobile phones, and electric vehicles. So here, the quality and the design of the product produced are very important. More and more industries can enhance their greener production and packaging capabilities using recycled materials to give a greener finish and label to the product while having minimal economic value. The focus must be to motivate the customers to buy more and more green products (Testa et al. 2021). According to Kansara et al. (2021), developing countries like China focus more on the knowledge-intensive industries that utilize GTI.

In some cases, the companies may focus on R&D to create innovations by taking certain risks due to more industrial competition, leading to reduced considerations toward GTI. So, it will be better to reduce their risk-taking tendencies and increase GTI activity (Yan et al. 2021). If GT is effectively used, the GT Innovation Efficiency (GTIE) will increase, leading the global value chain in a positive direction, one of the ways to increase sustainable economic growth (Kansara et al. 2021).

Next, it is very important to mention supply chain sustainability. Here the interest in green investment is always more from the retailer side than the supplier. For example, suppose we observe the case of battery suppliers. In that case, the electric car manufacturing companies will tell them to produce innovative green batteries, leading to reduced production costs and green battery technology. This will pressure suppliers to invest more in the production cost. Eventually, the manufacturing companies take the benefits. This later demotivates suppliers toward green investment (Wang et al. 2021a). Hence, it is necessary to maintain a good balance between the retailer and the supplier at the time of green investment (Wang et al. 2021a). The GT transfer and foreign investments significantly affect countries’ economic growth with green technological innovation for developing countries. There must be a good distribution of this technology to regional areas. Also, the crowding-out effect can create investments in science, technology, and education, improving regional competitiveness (Shen et al. 2021). Lastly, governments can work on increasing green nanoparticle (GNP) technologies. Nanoparticles have many applications and extensive usage in pharmaceuticals, biomedical, bioengineering, electronics, nuclear energy, etc. These green nanoparticles can be synthesized from plants, fungi, bacteria, and food waste products like rice husk to develop many green products—from medicines to developing nanomaterials for solar cells and electric batteries. Nanoremediation can be a good area for green investments and enhancing green technological innovations (Dutta and Das 2021).

**Sustainability transitions and space**

The changes in lifestyle and technology toward a greener, eco-friendly, and safe direction have motivated individuals, communities, governments, and the world to effectively transition toward a sustainable way of life. Following are some areas where a transition has been observed. Green housing is a significant way to enhance sustainable living. Using scientometrics and the green housing topic model, sustainable housing could be made into reality! These homes could be built using green materials, which are eco-friendly and durable. A ventilation system, sunlight, indoor greenery, and spacious rooms create an ideal sustainable and safe home (Kaklauskas et al. 2021). Another transition criterion can be green consumption. This entirely depends on an individual’s altruistic and biospheric values, concern for the environment, and green lifestyle orientation (Berman Caggiano et al. 2021).

In this case, the tendency of an individual to buy sustainable products and appliances is observed. If they care for the environment, they would prefer to buy eco-friendly appliances. For example, the individual prefers to buy LED lights instead of energy-consuming yellow lightbulbs. Here, the government and the industries developing these products must be entirely responsible for providing the correct green technologies to the consumers (Berman Caggiano et al. 2021). Another sustainable transition can be made at the industrial level, i.e., green composites; as research continued to create strong polymers, many improvements have been observed through cultivating different practices. Physical, chemical, biological, and chemical treatments make these materials/composites stable and durable. The two standout polymers are made from biomass and plant fibers. These both help increase the mechanical properties, facilitate degradability, and are antimicrobial. Plant fibers can be used to make ropes, textiles, mats, curtains, etc., which are eco-friendly and safe products (Vazquez-Nunez et al. 2021). Microalgae biomass is another highly effective and eco-friendly material with a fast growth rate, the ability to produce high oil yield, and is the most effective way for heavy metal pollution (Yap et al. 2021). It is a form of advanced GT with applications in the biopharmaceutical and nutraceutical industries (Yap et al. 2021).

GT can be effectively incorporated in manufacturing industries by operating milling, grinding, and other mechanical processes at green parameter settings, as Jibhakate et al.
In India, for example, production lines are created while producing goods; this is said to be one of the GT manufacturing practices and is known as a flow shop. By following these green parameters and practices, energy savings can significantly increase (Jibhakate et al. 2021). The extraction of rare earth metals like bastnaesite was done using HCl leaching, calcification roasting, and gravity separation. This led to a cleaner alternative to extracting rare metals. Other countries can utilize this sustainable method for fluorites, chlorites, and more (Cen et al. 2021). This shows how our economy is being shaped by knowledge capital and green innovation. Clean investments increase climate economics and create a resilient, zero emissions, and sustainable economy (Zenghelis 2021). Lastly, green entrepreneurship is the new transition toward a greener business model. It considers three pillars: technology, entrepreneurship, and ecological environment. Figure 4 gives a glimpse of the 12 model archetypes of green entrepreneurship that can be followed for the sustainable development of greentech businesses. These archetypes can provide a basis for many GT start-up companies to follow each model’s policies and put them into good practice. This can help create efficient and sustainable economies (Fig. 4) (Trapp and Kanbach 2021).

**Transitions, ecological modernization, and degrowth**

When the world is experiencing climate change, some significant transitions need to occur. We need to get back to the drawing board and formulate a new concept of growth, which is eco-friendly, green innovative, and sustainable. The points above have given us detailed information on the steps taken by the governments, industries, businesses, and individuals to save the environment since everybody has felt climate change and experienced it. Following are the practical transitions that will come into play like the green-based
active packaging of goods, urban resilience, rhizoremediation, the new concepts of analyzing the sustainable, circular economy, and how it can be improved. Some of the concepts included here are emergy analysis, industrial ecology, ecological modernization, and green artificial intelligence (GAI). As mentioned earlier, many industries focus on biodegradable packaging of goods, where green-based active packaging arises. After the COVID-19 pandemic, there has come a renewed opportunity to develop biodegradable packaging for food applications and help maintain a circular economy (Barone et al. 2021). These packages provide antioxidant, antimicrobial, and aromatic properties, which improve food quality and give a hygienic and safe food delivery, benefitting the customers. Green technological advancements have helped create these biodegradable packages using flexible biopolymers like plant fibers, biomass (starch and cellulose), and polyphenols (Barone et al. 2021). Urban resilience is the ability of a particular urban area to maintain its socio-ecological and socio-technical aspects across temporal or spatial considerations (Moglia et al. 2021). Here, the urban economy can be recovered by following the three urban missions—to attain urban mobility change, regenerative development, and create green infrastructure. A pathway series can create a process to build resilience and a green recovery in cities (Moglia et al. 2021). Next, rhizoremediation is a green and sustainable technique to treat or remediate contaminated soils using the symbiotic relationship between the plants and soil microorganisms. As per Hoang et al. (2021), this physiochemical technique is ineffective in treating soils contaminated with petroleum hydrocarbons (TPH). It requires biostimulation and bioaugmentation, i.e., mobilizing the soil microbes or rhizosphere microorganisms and increasing their catabolic activities, which helps in the effective removal of contaminants (Hoang et al. 2021).

When it comes to the concepts, the first one is emergy analysis. It is a measuring tool for economic, social, and environmental performance. It can help analyze sustainable supply chain management and circular economy (Alkhuzaim et al. 2021). This consists of a donor-side evaluation by considering the life cycle, sustainable performance assessments, and material flow analysis, i.e., how a particular institution does waste management and cost analysis. This can be a handy tool for researchers who wish to understand how sustainable production, performance, and consumption of GT are done by an institution (Alkhuzaim et al. 2021). The second concept, industry ecology (IE), is a bottom-up research approach that analyzes ecological, environmental, economic, and system dynamics. It solves industrial problems (Han et al. 2021). The third concept, ecological modernization (EM), is a European concept based on the top–bottom approach, which begins from the national level to results in environmental and social challenges. Sociologists mostly do this research (Han et al. 2021). Most of the published research papers focus on IE studies rather than EM since IE gives the scenario an overall image. At the same time, the EM still needs proper implementation. However, integrating IE and EM can clearly understand the ecological transition toward sustainable development and research (Han et al. 2021). Lastly, GAI provides holistic views on how AI can be used for smart cities in the fourth concept. Green sensing can help solve current urbanization issues and enable Industry 4.0 and smart cities toward sustainable solutions (Yigitcanlar et al. 2021).

Conclusion

The review discusses the connection between IR 4.0, conventional green processes, and the green economy. In the present scenario, GTs are an extraordinary challenge and lead toward the chance for new industries and provide competition among industries in the niche of the environment. Regarding the effect of the manufacturing and industrial endeavors on the environment, the green innovations and cycles are connected to Industry 4.0. They are a significant wellspring of sustainability for the future, as they bring together the social, economic, and environmental elements.

The vital commitment of this work for information and exploration is the arrangement that gives a characterization and structure to supportability the results of green cycles in the Industry 4.0 period. The sustainable outcomes of various GTs in the context of the Fourth Industrial Revolution have been brought into focus in this article while discussing global warming issues, the application of environmental biotechnology for a sustainable future, green chemical engineering, interactions of pollutants in the environment, product engineering to develop advanced biodegradable materials such as nanocellulose, biochar, starch, circular economy, and last but not the least the main goals of IR 4.0. There is also in-depth detailed information on the environmental economies that can help the governments to undergo green recovery most efficiently post COVID-19 and help maintain the reduced emissions of CO₂ and GHG. The vital enterprise processes should be advancing green design and manufacturing and the green supply chain and logistics. It is the proper and hypothetical groundwork for the experimental check of the interconnection between these ideas. The world’s governments can use the Green New Deal goals and strategies to create an eco-friendly transition using bio-based materials, hydroponics, and sustainable forest management. Technological developments that merged the Fourth Industrial Revolution and sustainability emphasized GTI and the IoT. It is in great demand today because of its multiplier effects that are beneficial in revolutionizing chemical engineering, product engineering, and the environmental industry. More products from advanced biodegradable materials need to be
developed to attain a sustainable environment for further headings of future studies. Fundamentally, the impediments of this study are considered in the ensuing investigations of the adverse consequence of the sustainability results. As inventors should know, green inventions and clean technologies are beneficial for business. These are profitable markets that are rapidly expanding. Green technologies can help consumers save money on energy expenses and are frequently safer and healthier than their non-green equivalents.

Acknowledgements The authors thank the VIT, Vellore, Tamil Nadu, India, for supporting this work.

Author contribution Conceptualization: K.R., B.V., and A.V.G.; resources and data curation: P.B., A.B., C.N., S.S., M.P., S.K., U.R.W., and A.G.M.; visualization: A.V.G. and K.R.; supervision: A.V.G. and K.R.; project administration: A.V.G., K.R., and B.V. All authors have read and agreed to the published version of the manuscript.

Funding This work was supported by the ICMR National Task Force Project [F.No. 5/7/482/2010-RBMH&CH].

Data availability The articles analyzed during the current study are available in the literature and listed in the references.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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