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Emerging Strategies in Greenhouse Gas Emission Analysis and Reduction: A Nanobiotechnology and Bioscience Perspective

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Abstract: The escalating challenge of greenhouse gas (GHG) emissions necessitates advanced methodologies for precise quantification and reduction strategies, crucial for bolstering climate resilience and shaping informed policy decisions. This review amalgamates insights from international studies and leverages nanobiotechnological innovations to present a multifaceted approach to GHG analysis. By harnessing intricate bioprocesses and nanoscale materials, we elucidate cutting-edge techniques to measure and quantify GHG emissions, with particular emphasis on carbon dioxide, methane, and nitrous oxide. The synergistic application of nanobiotechnological tools provides a deeper understanding of GHG dynamics, enabling more accurate assessments and developing novel reduction methodologies. The paper delves into the ecological impacts of GHG in the context of wastewater treatment and explores the role of nanotechnology in enhancing bioremediation processes. Moreover, it assesses the post-pandemic shifts in emission patterns, highlighting the pivotal role of sustainable nanobiotechnological advancements in mitigating environmental footprints. The research underpins the significance of biologically derived data in augmenting emission inventories' fidelity and formulating robust, science-backed climate actions. By integrating dynamic models rooted in nanobiotechnology with real-world applications, the study aims to serve as a cornerstone for future research endeavors, driving progress toward achieving global environmental targets and fostering the development of resilient, bio-informed climate policies.

Keywords: nanobiotechnology; emission; reduction; strategies; climate resilience; bioremediation processes; environmental policy development; GHG quantification.

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1. Introduction

Some gases in the atmosphere, both naturally occurring and those produced by humans, are known as greenhouse gases because of their ability to absorb and re-emit certain wavelengths of the thermal infrared radiation that is naturally and artificially released by the Earth's surface, atmosphere, and clouds [1,2]. Because of rising anthropogenic activity mixed with population growth, the quantity of gases like CO_2, CH_4, N_2O, and CFCs collectively known as Greenhouse Gases (GHG) in the atmosphere has hastily grown, resulting in a large increase in soil temperature. Due to increased anthropogenic activity, the concentration of greenhouse gases (GHG) in the atmosphere has increased quickly in the previous century, resulting in a major increase in the Earth's temperature and global warming. The sun's energy is absorbed by these gases, warming the lower atmosphere and causing the phenomena known as the natural greenhouse gas effect.

Forests (because of human-caused changes in the Earth's roof that promote deforestation), energy production (fossil fuel combustion), transportation (fossil fuel combustion), and agriculture are the main producers of greenhouse gases (animal husbandry, agriculture, rice). Crop residues (planting and burning), wetlands, aquatic bodies, industrial operations, and urban activities (construction, transportation, solid and liquid waste). By converting greenhouse gases (CO_2 and non-CO_2) into carbon dioxide (CO_{2e}) equivalents, a Green House Gas footprint may be determined. As a result, the greenhouse gas footprint is a measurement of the amount of greenhouse gases created by human activities on the environment. CO_2 is the most important GHG in global warming, accounting for over 77% of total global GHG emissions equal to CO_2 [3].

1.1. Various greenhouse gases.

The list of GHGs includes gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorinated fluorocarbons (CFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), tetrafluoromethane (CF_4), and others. CO_2, CH_4, and N_2O, the first three gases, are natural and anthropogenic. The only source of the remaining gases is human activity. Due to the fact that they enter the atmosphere via industrial processes, these gases are called "industrial gases" as well.

Evaluating carbon footprints in terms of greenhouse gas emissions, energy consumption, energy production, and carbon credits is fascinating [4]. In order to calculate the amount of greenhouse gases (GHGs) released by various sectors, it is necessary first to compile a list of all of the gases that are released and then assign each gas the appropriate GWP. A GHG's global warming potential (GWP) is the amount of heat trapped per unit mass of the gas relative to CO_2 over a certain time period (typically 100 years). Table 1 below includes the global warming potential values for several of the gases [5].

Table 1. The global warming potential of greenhouse gases [5].

Name of Gas	Name of chemical	Global warming potential
Carbon Dioxide	CO_2	1
Methane	CH_4	27.9
Nitrous Oxide	N_2O	273
CHC-11	CCl_3F	5560
HFC-21	$CHCl_2F$	160
Methyl chloroform	CH_3CCl_3	161
Carbon tetrachloride	CCl_4	2200
Chloroform	$CHCL_3$	20.6
Chloroethane	CH_3CH_2Cl	0.481
Methyl Bromide	CH_3Br	2.43
Nitrogen trifluoride	NF_3	17400
Ethane	C_2H_6	0.437
Propane	C_3H_8	0.02
Butane	n-C_4H_{10}	0.006

The GWP varies widely for different gases. As a result, the emission of a small quantity of a high GWP gas has a bigger impact on the environment than the release of a similar quantity of a low GWP gas. For instance, the heat-trapping potential of one kilogram (kg) of released N_2O is equal to 273 kg of CO_2 [5-8]. There are several models that may be used to calculate GHG emissions. On the one hand, it is possible to measure emissions as an average value over a certain period of time using empirical static models [9,10]. On the other hand, there are available specialized mechanistic models that can dynamically characterize the operation of activated sludge systems, e.g., Activated Sludge Model 1, if we deal in the wastewater treatment sector. GHGs can be incorporated into these models as state variables. The concentration and GWP of GHGs define each one's specific contribution to global warming.

1.1.1. Carbon dioxide.

Between 2000 and 2010, 76% of human-caused greenhouse gas emissions were carbon dioxide, according to the IPCC [11]. Hence, carbon dioxide is the most significant greenhouse gas in climate change. To fight global climate change, nations are reducing their CO_2 emissions. The Paris Agreement, signed in 2015, aims to limit global warming to 1.5 degrees Celsius above pre-industrial levels. "Nationally determined contributions" have pledged to reduce carbon dioxide emissions [12,13]. Preliminary observations indicate that CO_2 quantity was significantly lower during the preceding Ice Age than over the last 10,000 years of the Holocene. From 10,000 years ago to 1750, CO_2 levels varied between 280±20 ppm. CO_2 levels climbed significantly during the industrial era, reaching 367 parts per million in 1999 and 379 parts per million in 2009 [14].

1.1.2. Methane.

Methane (CH_4), another greenhouse gas (GHG), contributes to global warming and climate change. The decomposition of organic materials in wetlands and the digestive processes of ruminant animals, as well as anthropogenic activities that produce significant amounts of methane into the atmosphere, include the production of fossil fuels, cattle enteral fermentation, management of mature, rice farming, burning of biomass, and management of waste [15,16]. Human-caused methane emissions account for over half of worldwide methane emissions [17]. Methane and nitrogen oxide levels saw dramatic increases in the twentieth century after being stable at 700 parts per billion (ppb) until the nineteenth century. Methane concentrations increased steadily, reaching 1745 ppb in 1998 and 1774 ppb in 2005 [18]. Methane emissions must be reduced to delay climate change globally. Livestock production can be improved, methane emissions from landfills and waste management facilities can be caught and utilized, oil and gas output can be lowered, and natural gas production and distribution may be optimized. These are several methane reduction methods. Cutting methane emissions may improve air quality, reduce local environmental impact, and increase energy efficiency. Many methane emission reduction methods may generate revenue by recovering methane for electricity production or selling carbon credits.

1.1.3. Nitrous oxide.

Natural sources and human actions both produce nitric oxide (N_2O). The most important anthropogenic sources include managing agricultural soil, managing manure from animals, treating wastewater, burning fossil fuels (both vehicular and stationary), and generating nitric acid [19]. Numerous biological activities in soil and water also contribute to the production of nitric oxide, most notably microbial effects on N_2O measurements, with relatively modest increases over the industrial period (15 percent). The concentration was 314 ppb in 1998 and 319 ppb in 2005 [20,21].

1.2. Emissions from various sectors globally.

In order to study the effects of emissions from various sectors, Table 2 below gives a numeral view of the share of the percentage of greenhouse gas emissions from various sectors globally. The table represents the emission percentage from the energy sub-sectors.

Table 2. Contribution of various sectors in greenhouse gas emissions [22,23].

Sector	Emission (%)
Energy(Electricity, heat and transport)	73.2
Direct industrial processes	5.2
Waste	3.2
Agriculture, forestry, and land use	18.4

Table 3 summarizes the emission shares of various sub-sectors within key sectors such as energy, industrial processes, waste, agriculture, forestry, and land use. These figures highlight the significant contributors to global greenhouse gas emissions across different economic activities [24]. Understanding the distribution of emissions across these sub-sectors is crucial for designing targeted mitigation strategies.

Table 3. Emission shares of sub-sectors of energy, industrial processes, waste, agriculture, forestry, and land use sector [24].

Sub-sector	Share of global greenhouse gas emissions (%)
Transport	16.2
Energy in buildings (electricity and heat)	17.5
Energy in industry	24.2
Energy in agriculture and fishing	1.7
Unallocated fuel combustion	7.8
Fugitive emissions from energy	5.8
Cement	3
Chemical and petrochemical (industrial)	2.2
Livestock and manure	5.8
Rice cultivation	1.3
Agricultural soils	4.1
Crop burning	3.5
Forest land	2.2
Cropland	1.4
Grassland	0.1
Landfills	1.9
Wastewater	1.3

1.3. Trends in the emissions of greenhouse gas.

From Figure 1 (constructed using the data extracted from [25]), it can be observed that in 2021, the world's carbon dioxide (CO_2) emissions rose to a record high, driven by a revival in energy combustion and industrial operations. The IEA predicted that since 2020, emissions had grown by 6%, amounting to 36.3 gigatonnes (Gt), in the most current calculated data report [25,26]. This estimate was derived from the most recent official national statistics as well as publicly accessible energy, economic, and climatic factors. The widespread impacts of the COVID-19 epidemic on energy demand resulted in a 5.1% decrease in worldwide CO_2 emissions in 2020.

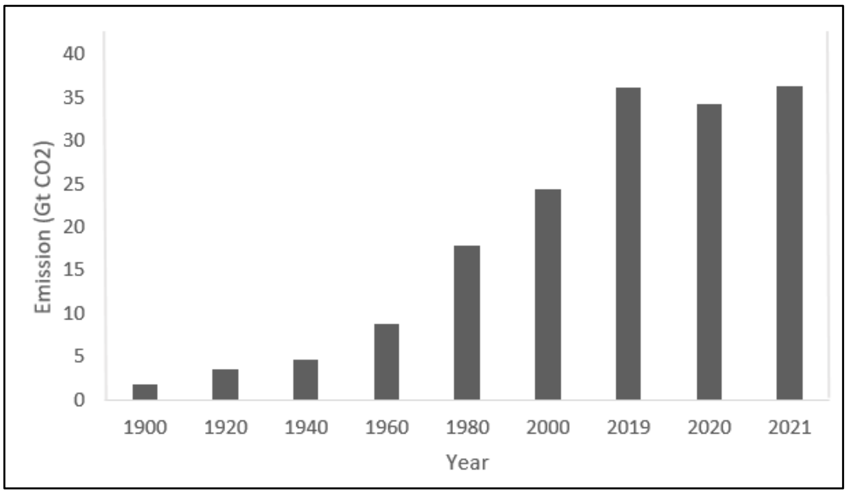

Figure 1. Total CO_2 emissions from energy combustion and industrial processes, 1900-2021.

Meanwhile, the global economy has rebounded fast since then, aided by massive monetary and fiscal stimulus and the rapid deployment of vaccinations worldwide [27-29]. The recovery in energy demand in 2021 was worsened by harsh weather and unfavorable energy market circumstances, which led to more coal being burned despite renewable electricity generation recording its largest yearly gain of more than 2.0 Gt added to emissions from their 2020 levels. Emissions dropped by nearly 1.9 Gt in 2020 due to a pandemic, but they bounced back strongly the following year (2021). In 2021, CO_2 emissions were roughly 180 Mt higher than the 2019 pre-pandemic level. The IEA calculated that 2050 emissions would have grown by 6%, totaling 36.3 gigatonnes, using the most up-to-date approved national statistics and publicly accessible energy, economic, and climatic data [30].

1.4. Greenhouse gas emissions from various sectors in India.

During the period of 1990 to 2014, there was a huge accumulation of Greenhouse gas emissions from various sectors, which accounts for around 2,060 $MtCO_{2e}$ increase, which means it is almost 180 % fold in the increase of the emission. During the same phase, India's GDP growth was around 357 %, leading to a 180 % increase in GHG emissions and making India the third most GHG emitter in the world [31,32].

As per the Indicators of Climate Analysis from the World Resources Institute (WRI CAIT), In 2014, the energy sector was responsible for 68.7% of India's total emissions [33], making it the dominant contributor to the country's greenhouse gas profile. Heat and power generation account for 49% of energy sector emissions, with generation and construction accounting for 24% each. Enteral fermentation accounted for 45 percent of agricultural emissions, making agriculture the second largest source of emissions (19.6 percent overall). Some 6.0% of all emissions came from industrial processes (IP), 3.8% from land use change and forestry (LUCF), and 1.9% from garbage [34].

1.4.1. Power plants.

Greenhouse gas emissions are produced during the complete power generation process. India's heavy dependence on fossil fuels for power production has contributed to the country's already high carbon dioxide (CO_2) emissions from its energy sector [35]. When coal is burned in thermal power plants, it releases a number of harmful pollutants, the most notable of which are carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x) [36]. Energy consumption for home and commercial purposes, such as cooking, lighting, and heating, contributes to emissions. There were 137.84 million metric tonnes of CO_2 equivalents released by the residential sector in 2007, whereas only 1.67 million metric tonnes were emitted by the business sector at the national level in 2007.

1.4.2. Transportation.

The rise in emissions from the transportation sector can be traced back to an increase in the number of cars on the roads and the distances they travel [37]. Many advanced data collection techniques have been developed for collecting traffic data, such as vehicle class and speed, which are indirectly linked to emissions based on various classes of vehicles [38]. The amount of gasoline and diesel used is directly proportional to the amount of emissions produced. Emissions of CO_2, CH_4, and N_2O, as well as ozone-depleting gases, including CO, NO_x, and NMVOC, were analyzed for the Indian road transportation industry from 1980 to 2000 [39]. Emissions have been calculated in various research studies by looking at factors such as activity levels, vehicle miles driven, vehicle types, and vehicle subcategories. Fuel emissions (FE) in Gigagrams/day (Gg/day) are calculated by multiplying vehicle pollutants (grams/Km) by the average distance traveled and the total number of vehicles [40]. The Central Pollution Control Board, state pollution control agencies, and the Ministry of Environment and Forests collaborated with the Automotive Research Association of India to create emission factors for Indian automobiles.

1.4.3. Industries.

The industry is a significant contributor to global greenhouse gas emissions. The industrial sector accounts for around one-third of global carbon dioxide emissions [41-42]. Numerous studies have attempted to determine the amount of carbon dioxide released during manufacturing iron and steel, cement, fertilizer, and other industries, including lime production, ferroalloy fabrication, and aluminum production [43].

1.4.4. Agriculture.

Methane (CH_4) emissions from rice cultivation with irrigation, nitrous oxide (N_2O) emissions from nitrogenous fertilizers, and carbon dioxide (CO_2) emissions from energy used to pump groundwater for irrigation are the primary agricultural sources of greenhouse gases [44-46]. The combustion of biomass emits a significant amount of CO_2. In India, agricultural waste from the fields is used as cow fodder home biofuel, and the rest is burned in the fields [47]. Agricultural systems will be under tremendous pressure to increase food production sustainably as the world's population is projected to nearly double to 10 billion by 2050 [48,49].

1.4.5. Waste sector.

Methane is the principal GHG released by waste treatment plants. It is produced when methanogenic bacteria digest organic matter in garbage without oxygen and release the resulting gas into the environment. Similarly, when wastewater is processed or disposed of anaerobically, it becomes a source of CH_4. Because of the protein concentration in domestically generated wastewater, it has the ability to release nitrogen oxides [50,51].

2. Methodologies to Estimate GHG Emission

In this section, various methodologies of estimating GHG emissions have been discussed and taken in reference to many international agencies and the literature of many researchers.

2.1. Water Environmental Federation.

The assessment of GHG emissions, especially from wastewater treatment plants, is addressed in a new Technical Practice Update (TPU) published by the Water Environment Federation [52]. Standards for reporting greenhouse gas emissions are summarized, along with brief explanations of the procedures produced by a number of significant organizations [53,54]. WEF collects data from the protocols and other applicable field observations to refine its estimation methodologies and emissions factors, allowing for a more precise characterization of emissions at the local facility level in relation to specific operating parameters [55,56]. The process for compiling GHG emission inventories was standard across the board. The steps in the technique are to choose a base year, set inventory boundaries, identify effluent discharge quality, classify the sources of GHG emissions at the facility, and then quantify the emissions in terms of CO_2 equivalent [57-59].

2.2. U.S. Environmental Protection Agency (US EPA).

The United States Environmental Protection Agency provides guidelines in two sections for calculating greenhouse gas emissions from sewage treatment facilities [60,61]. The Intergovernmental Panel on Climate Change (IPCC) believes there is no room for CO_2 emissions when only biogenic sources are considered [62]. There are four scenarios in which CH_4 may be released from either on-site treatment facilities (like septic systems) or off-site centralized treatment systems (like publicly owned treatment works) (POTWs).

Table 4. Scenarios for different types of systems used for wastewater treatment.

S.No	Type of System used
I	Septic tank
II	Centrally treated aerobic
III	Centrally treated anaerobic
IV	Anaerobic digester

When estimating N_2O emissions from wastewater treatment in the home, the US EPA uses the same approach as the Intergovernmental Panel on Climate Change (IPCC 2006).

The aforementioned methods use a standardized technique to compile GHG inventories at the national and regional levels [63]. All of these approaches use a standardized mechanism to compile regional or national GHG emission inventories that factor in a number of different variables to predict total GHG output, waste-generating potential, and other social and cultural practices of the country or region included for GHG inventories are extremely varied. Although they have an effect on greenhouse gas emissions, these considerations are typically overlooked in GHG inventories. The climate of Shimla, for instance, is quite different from that of Rajasthan, India. Nevertheless, a true picture of global GHG inventories cannot be obtained by using a country-specific emission factor for India. Since the physical, chemical, biological, and microbiological processes involved in the wastewater route, wastewater treatment, and effluent disposal system are ignored, these methods overstate GHG emissions from wastewater. For instance, the IPCC's approach does not take into consideration the solutions established to reduce emissions of greenhouse gases from sewage treatment plants [64,65]. The above-mentioned method for GHG emissions inventories is only useful as a guiding factor to access and plan for control of GHG emissions. Therefore, they are better suited for the national or regional GHG inventory computation or estimation than the plant or process-level estimation. Indeed, the aforementioned claim is corroborated by Yerushalmi *et al*. 2011 [66]. One of the major problems with this assumption is that wastewater treatment facilities often ignore CO_2 emissions that come from the biogenic decomposition of biomass, food waste, etc. [67,68]. Therefore, the aforementioned procedures might not work for determining the amount of greenhouse gas emissions a certain wastewater treatment plant is responsible for. It's important to note that producing biomass or food almost never occurs without the utilization of fossil fuels. Consequently, wastewater's CO_2 emission from the decomposition of organic waste may be counted toward the GHG emission total [69,70]. The production, transmission, and delivery of the energy and materials used in WWTPs all result in greenhouse gas emissions. However, GHG emissions from the waste sector for energy and material use are not included in the inventories recommended by the aforementioned approaches. In light of this, it is clear that the above inventories cannot be relied upon to provide a reliable forecast of GHG emissions within the sector. Because of their very nature, wastewater treatment facilities release greenhouse gases during the course of their operations. Wastewater treatment plants have been identified as particularly susceptible to Kyoto and later protocols' imposition of taxes and penalties on GHG emissions. Reducing greenhouse gas emissions and avoiding potential carbon GHG levies necessitate an abatement strategy foundation for the wastewater treatment facility [71]. Wastewater treatment facilities might switch to carbon-saving treatment methods so they can earn carbon credits. Determining the most important process factors regulating GHG emissions will make optimizing the WWTPs' process parameters and operating conditions possible. In light of the foregoing, a number of studies have proposed adjusting WWTPs' process parameters and operating conditions to cut back on greenhouse gas emissions [72,73].

2.3. Methodologies for estimation of greenhouse gas from the transportation sector.

This section represents various methodologies adopted for estimating GHGs like carbon dioxide, methane, and nitrous oxide from various sectors. The literature used in this paper has been taken from various reputed research papers that have been peer-reviewed. Various methodologies have been used in this literature to estimate methane, carbon dioxide, and nitrous oxide.

Yihui Tian *et al*. [74], in their paper titled "Analysis of greenhouse gas emissions of the freight transport sector in China, " used two steps for calculating the greenhouse gases from freight transport. First, the energy consumption of freight transit in various Chinese regions was calculated using an equation stated as provided in Eq. 1.

$E^i_{j,k} = V^i_{j,k} CF_{j,k}$ (1),where the energy consumption of the freight transport sector is represented as $E^i_{j;k}$. The Chinese provincial region, which includes provinces, autonomous regions, and municipalities directly under the central government, is denoted by the superscript i. Railways, highways, waterways, air transportation, and oil pipelines are all represented in subscript j. Electric locomotives, steam locomotives, diesel locomotives, gasoline trucks, diesel trucks, inland ships, coastal ships, airplanes, and pipelines are all represented by the subscript k. $V^i_{j;k}$ denotes the freight turnover of transport vehicle k in region I under transport mode j;

[75]. Figure 2 shows the various modes of transportation, and along with the subcategories of various modes, the main source of their energy is mentioned.

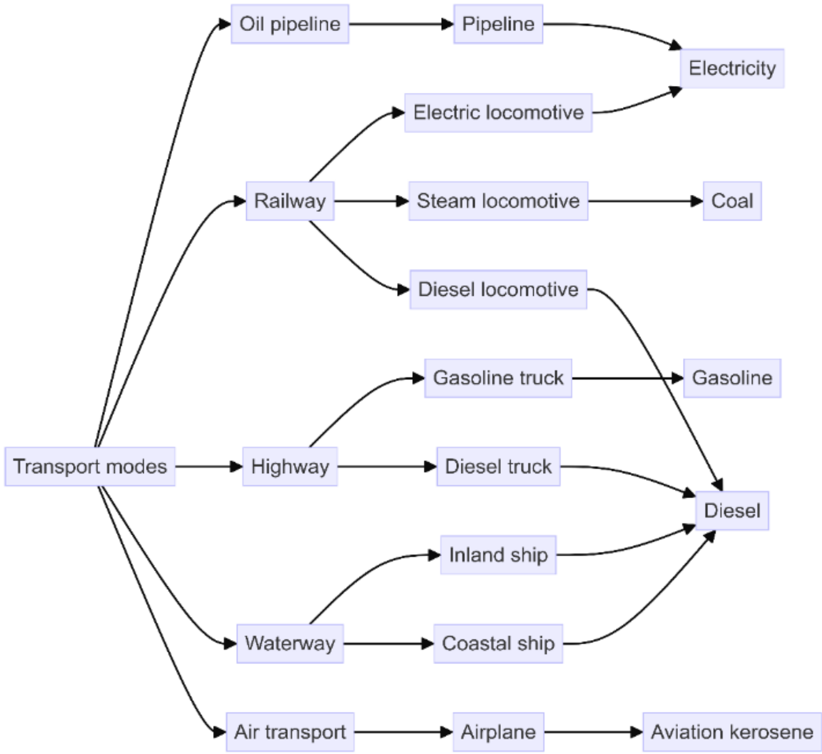

Figure 2. Various modes of transportation and their source of energy.

Wang's study, which summarised and handled data from several Chinese statistics yearbooks and other related policy files, demonstrates that energy consumption factors for various vehicles imply energy consumption per unit of freight turnover [76].

Second, based on the aforementioned data, different cars' For China's greenhouse gas inventory, the International Protocol on Climate Change (IPCC) has developed national recommendations. Because carbon content and GHG emissions vary by energy source, CO_2, CH_4, and N_2O are examined as carbon dioxide equivalents (CO_{2e}). The IPCC cites GWPs of 1, 21, and 310 for CO_2, CH_4, and N_2O, respectively [77,78]. The quantity of oxidized carbon and energy consumption of a vehicle are two of the most important parameters to consider when calculating the amount of greenhouse gas emissions it produces [79].

It was seen in this paper that the GHG emissions in China's freight transport sector jumped six times from the year 2000 to 2011 because of the rapid growth in China's freight. Proportions of emissions from various sectors of transport were calculated and stated in percentage form. In 2000, the proportions of GHG emissions from these five modes of transportation, which included railways, highways, waterways, aircraft, and oil pipelines, were 7.3 percent, 53.0 percent, 31.9 percent, 7.2 percent, and 0.6 percent, respectively.0. In 2011, they were 2.4 percent, 82.9 percent, 11.3 percent, 3.0 percent, and 0.3 percent [80,81]. The figure below shows the graphic data from which the distribution of various GHGs was given for 2000 and 2010, respectively.

Pandey *et al*. [82], in their paper " Estimating emissions from the Indian transport sector with on-road fleet composition and traffic volume," worked on the emission estimations for various modes of transportation based on an overall framework that took into account the fuel used in each mode, which was allocated among technology types, as well as the relevant emission factors. An equation was developed linking the energy consumption in terms of fuel consumed by each mode of the vehicle and the emission factor, which is given by Eq. 2:

$$E_m = \sum_{f,t} F_{m,f,t} \times EF_{m,f,t} \quad (2)$$

Where E_m applies to total emissions in Gg/y from mode m, and $F_{m,f,t}$ and $EF_{m,f,t}$ are the fuel consumption in MT/y, and emission factor in g/kg fuel burned, for fuel type f and combustion technology t within that mode. To estimate fuel consumption across different modes of transport, top-down and bottom-up methods are used, which are based on either nationally reported fuel consumption in the mode or a detailed consumer survey of technology units in the mode of transport. Methods were based on the amount of fuel used by the various modes of transport. Road transport uses the maximum fuel, so the bottom-up method was used, whereas the railways and aviation sectors were analyzed using a top-down approach to be less consumer than the road sector. For finding vehicle emissions, the tier III approach of IPCC was used so that vehicle efficiency, age of vehicles, and advancement of technology can be included. Consequently, with this approach, the standard emission factor of IPCC 2006 emission factor for the tier III approach was used [82].

Y. Charabi *et al*. [83], in their paper," GHG emissions from the transport sector in Oman: Trends and potential decarbonization pathways," used guidelines and methodology developed by IPCC 2006 [83]. This guideline, which was developed to allow states to report their respective national greenhouse gas emissions, was written with the United Nations Framework Convention on Climate Change as the intended audience in mind when it was being drafted (UNFCCC). The IPCC Guidelines from 2006 organized the GHG inventory emission approaches based on three levels of the required amount of data and the degree of complexity of the analysis: low, medium, and high. I Tier 1 is the default strategy that is based on IPCC emission factors and utilizes national average data that are appropriate to estimate the amount of emission generated by each source category. This technique is referred to as the "source category method." "Tier 1" is the name given to this particular approach. (ii) Tier 2 is an intermediate degree of information and complexity, and it is based on national emission factors that were developed based on data from certain nations. This level is based on national emission factors that were produced based on data from certain countries. In general, Tier 2 activity data is obtained by estimating or modeling in a way that accurately depicts the local change in use or behavior. This may be done in a number of different ways. The vast bulk of the data supports this interpretation. (iii) The most comprehensive approach is referred to as Tier 3, and it requires the use of fuel-burning technology in addition to adhering to country-specific emission requirements for each gas. For calculation context, IPCC inventory software version 2.69 incorporated the Tier 1 approach, as shown in Figure 3. The transportation industry is a subsector of the combustion activities industry. It incorporates many subcategories of transportation, including civil aircraft, transportation by road, railroads, water navigation, and other transportation. The global warming potential from the fifth IPCC assessment report was used to calculate the CO_2 equivalents of the non-CO_2 gas emissions for the purpose of this research. The time horizon for this calculation was set at 100 years.

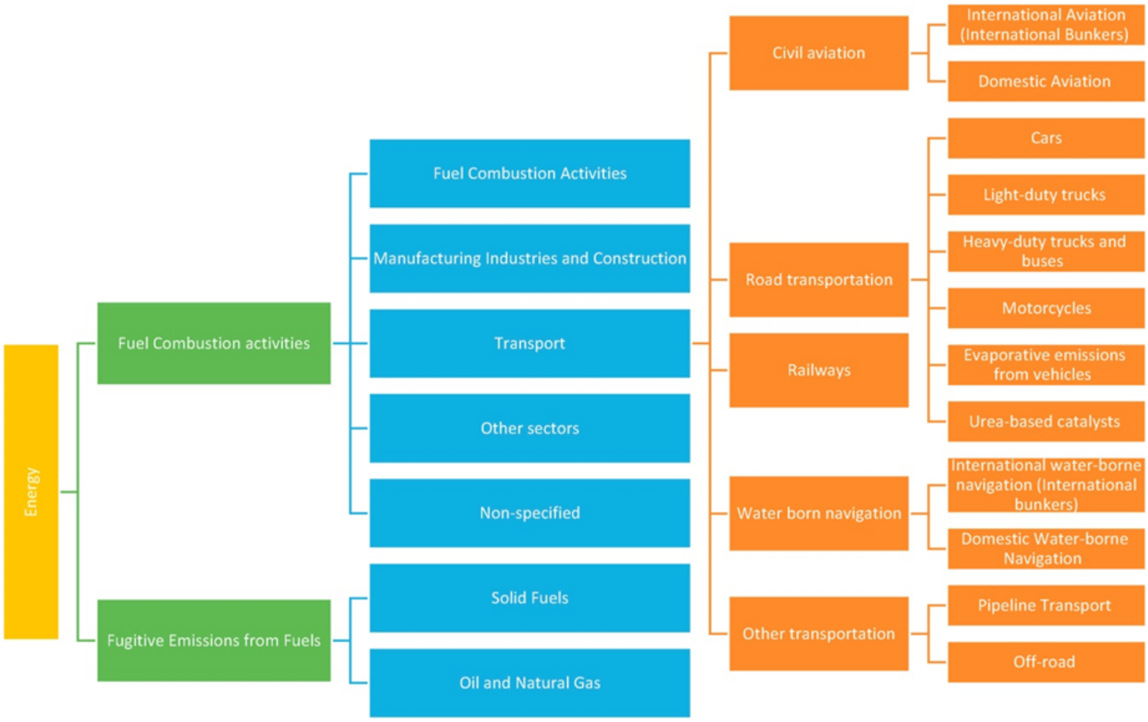

Figure 3. Subcategories of the energy sector in the IPCC GHG inventory software are available in version 2.69

2.4. Methodology from various literature in the field of wastewater sector and sanitation practices.

Bridle identifies sludge treatment, bio-treatment, chemical use, power consumption, and biogas production as the five parts of a wastewater treatment system that produce greenhouse gases. Individual empirical models were proposed for each segment to use in estimating GHG emissions [84]. Bridle has provided a thorough model for bio-treatment, which includes the three phases of GHG production—decay of endogenous biomass, oxidation of biochemical oxygen demand (BOD), and removal of nitrogen. Chemical usage emissions are also accounted for in the full model. The model is capable of producing credible estimates of GHG emissions. Anaerobic digestion and the reuse of sludge are the processes that emit the most greenhouse gases. Dynamic and more accurate modeling of the N_2O emission is possible [84].

The method for estimating GHG emissions from municipal wastewater treatment plants was established by Montheith *et al*. (2005) [84]. The method can be used to estimate carbon-based GHG emissions per cubic meter of treated wastewater for various processes, and it can be applied either with plant-specific data or with more general regional data. A municipal wastewater treatment facility emits mostly carbon dioxide and negligible methane. The method was tested using data from 16 Canadian wastewater treatment plants and then implemented across 10 provinces. Methodology pinpoints the potential for cutting greenhouse gas output at sewage treatment plants in urban areas. Suitable inputs and the system boundaries were determined prior to using the technique. Both scenarios where plant-specific data is and is not accessible were considered, and methods for calculating GHG emissions were created accordingly. Serialized calculations, created for use when no plant-level data is available, were compared to the GHG emissions calculations performed with plant-level data. The primary greenhouse gases considered in this technique are carbon-based, specifically CO_2 and CH_4. Emission of N_2O, a form of GHG produced by sewage treatment facilities, has not been factored into the methodology under consideration. However, the author has proposed doing more work to estimate N_2O at treatment plants to understand its GHG potential better. Carbon-based GHG emission calculation is constrained to within-system treatment methods. Using this method, we can see that carbon dioxide is by far the most abundant GHG released by Canadian facilities. Combustion of methane released during anaerobic digestion of materials results in carbon dioxide, reducing the efficacy of CH_4 relative to CO_2. Off-site electricity generation used by the treatment plant, solids transportation and degradation, chemical production and degradation, and treated effluent disposal are not factored into the GHG emissions calculated using this method [86,87].

The methodology developed by Shahabdai *et al*. [87] or the estimation of GHG emission explained a mathematical model that takes into account both on-site and off-site operations of a wastewater treatment facility to arrive at an overall estimate of GHG emissions from all treatment processes (aerobic, anaerobic, and hybrid - anaerobic/aerobic). Due to a lack of data, the emission estimation technique can only provide estimates for CO_2 and CH_4 production, both on- and off-site and not N_2O emission. Global warming potential emissions from off-site power use for things like reactor liquid mixing, plant lighting, and appliance use. For this reason, CO_2 emissions based on power use in the plant have been accounted for using the emission factor for the electricity-producing source.

The off-site source of greenhouse gases was determined to be the breakdown of leftover bio-solids in digester effluent. Emissions of greenhouse gases have been studied in relation to biogas recovery and use. The team has also looked at the impact that nutrient deficiency has on the release of greenhouse gases. It was shown that an aerobic treatment system produces more CO_2 equivalent emissions each day than it consumes in the form of energy consumption, suggesting that the on-site GHG emission is greater than the off-site emission [87]. Compared to aerobic treatment methods, the results from anaerobic and hybrid systems were distinct. The results showed that off-site GHG emission was greater than on-site emission for both anaerobic and hybrid treatment methods. In addition, the authors offer GHG reduction strategies commensurate with the results, such as the recovery and use of biogas for energy production as a replacement for the burning of fossil fuels. The authors recommend moving from a mesophilic or thermophilic treatment to a psychrophilic one for your digester if you wish to lessen its environmental impact. The authors recommend using anaerobic processes like anammox to extract nitrogen from wastewater with reduced energy and carbon usage to reduce greenhouse gas emissions [89].

Utilizing their own methodology, Yerushalmi *et al*. [66] looked at how several processes—aerobic, anaerobic, and hybrid—affected GHG emissions locally and globally. The most crucial process parameters were found to be SRT, reactor, and sludge digester temperatures, as well as the underflow rate in the main clarifier. Most strongly correlated with the anaerobic sludge digester operating temperature is the GHG output from the aerobic treatment system. The research team behind this study has proposed several changes that might be made to existing treatment process systems in order to reduce their contribution to global warming. Reduce the quantity of greenhouse gases emitted during aerobic treatment by raising the BOD removal ratio in the primary clarifier and reducing the VSS removal ratio. The treatment system's greenhouse gas emissions may be lowered by optimizing the waste ratio in the anaerobic reactor. The main clarifier's VSS and BOD removal ratios may be lowered, the anaerobic reactor's SRT and wasting ratio can be raised, and the anaerobic digester's SRT can be lowered to lower GHG emissions [90].

Wang *et al*. [94], in their paper," Carbon source recovery from waste sludge reduces greenhouse gas emissions in a pilot-scale industrial wastewater treatment plant," discussed how the Greenhouse gas emission can be reduced in order to attain sustainability by presenting a pilot project study on a waste treatment plant. This study reflects the investigation done on a pilot scale project in which a handsome amount of carbon was recovered primarily from PS (Primary Sludge) through a short period (5 days) of acidogenic fermentation. Then, the recovered carbon was consequently used at the wool processing industrial wastewater treatment plant for denitrification. It was also seen that the recovered carbon from PS were very good electron donors that can be used as a supplement for commercially utilized glucose for enhancing denitrification [91,92]. The Dongfang wool processing industrial WWTP in Shandong, China, served as the location for the pilot study's implementation.

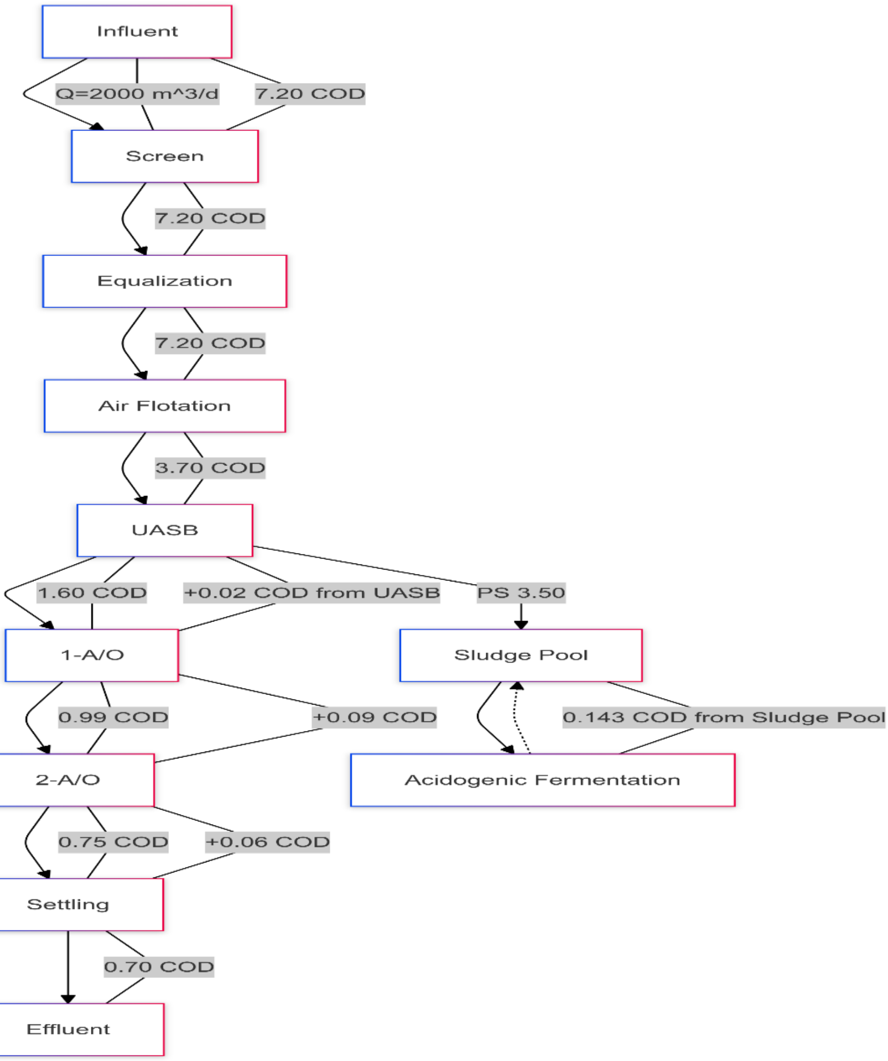

Figure 4. The carbon flow balance at the wastewater treatment plant facility is used by wool processing.

This WWTP offers services to a central wool industrial park with a daily wastewater discharge quantity of 2,000 m^3. The wool processing industry generates wastewater with both a high level of suspended solids (SS) and a high amount of chemical oxygen demand (7200 mg /L). The industrial WWTP's process design included a flotation tank, an up-flow anaerobic sludge blanket (UASB) reactor, a two-stage tandem anoxic/oxic (A/O) reactor, and a secondary sedimentation tank. The flotation tank was the initial element of the process system [93,94].

Figure 4 shows the carbon flow balance at the wastewater treatment plant facility used by the wool processing sector (WWTP). The amounts 1.68, 0.31, and 0.26 shown at the top of the chart represent the total quantity of chemical oxygen demand (COD) that has been discharged into the environment in the form of a gas. The quantity of chemical oxygen demand (COD) that was transferred to the sludge is shown by the numbers 3.50, 0.45, 0.39, and 0.50 at the bottom of the graph, while the arrows in red point to the sludge pool [95]. The red numbers show an imbalance in the COD, and the asterisk indicates that the COD has been enhanced by carbon sources that come from outside the system.

2.5. Nanobiotechnological enhancement of GHG dynamics understanding.

Using nanobiotechnological tools has revolutionized the field of environmental sciences, particularly in understanding and managing greenhouse gas (GHG) emissions. Nanotechnology, when applied to biological systems—nanobiotechnology—offers unprecedented precision in detecting and quantifying GHG emissions [96]. This synergy enables the development of highly sensitive biosensors capable of tracking emission dynamics at a molecular level, facilitating real-time monitoring and assessment. These advanced biosensors, composed of nanomaterials like carbon nanotubes, graphene, and quantum dots, provide enhanced reactivity and selectivity towards GHG molecules such as CO_2, CH_4, and N_2O. Nanobiotechnological applications also extend to creating nanostructured catalysts that can potentially convert GHGs into less harmful substances or even usable energy sources [97,98]. Furthermore, nanoscale materials can improve the efficiency of bioreactors that play a pivotal role in biosequestration processes, thereby enhancing the natural absorption rates of GHGs by microorganisms.

Incorporating nanotechnology into bioremediation strategies opens new pathways for the biodegradation of GHGs. The manipulation of enzymes and pathways at the nanoscale can accelerate the breakdown of GHGs, leading to more efficient waste treatment processes with lower emissions [99,100]. Additionally, nano-enabled bioprocesses can be tailored to target specific GHGs, offering a tailored approach to emission reduction.

3. Conclusions

At WWTPs, GHG emissions occur at a number of points throughout the processing cycle. Therefore, it is important to keep track of and quantify GHG emissions. Many organizations and agencies have worked to achieve this aim by creating static and dynamic mathematical models and approaches. It is possible that the IPCC's 1997 and 2006 proposals were the first thorough methodology or recommendations for assessing greenhouse gas emissions. Based on the ease of access to relevant data, IPCC 2006 proposes three different methods (tiers 1, 2, and 3). WRI USA's web-based interface program estimates sector-by-sector country-level GHG emissions to make estimating simpler. Since wastewater treatment plants are often the source of greenhouse gas emissions, the Water Environment Federation has also produced a Technical Practice Update (TPU) for this purpose. To further characterize local facility-level emissions based on particular operating parameters, WEF (2009) utilizes data from the Climate Registry (TCR), the ISO 14064 GHG standard (2006), and other organizations, as well as pertinent field observations. When it comes to estimating greenhouse gas emissions (GHG, CH_4, and N_2O) from the process of treating residential wastewater, the United States Environmental Protection Agency (EPA) has proposed splitting the corresponding mathematical equations into two independent portions. A strategy like the one proposed by the US EPA is consistent with that of the IPCC. Due to its biogenic origins, the evaluation of CO_2 emissions caused by the breakdown of organic waste in WWTPs is not endorsed by any of the aforementioned organizations.

In the transport sector, major emissions are from the highway sector, i.e., road transport, in which the emissions are due to the use of gasoline and diesel in cars, trucks, and bikes. For the emissions from the transport sector, most of the methodologies adopted are based on the IPCC guidelines. In most of the studies, emission factors have been directly taken from the IPCC guidelines, and in some of the studies, country-specific data were used; such country-based data proved to be more accurate in studying the emission quantification of GHGs for futuristic scenarios. In a nutshell, in both the transportation sector and wastewater treatment plant and another sector, quantification of GHGs has been done using IPCC guidelines as the base model, and correspondingly, different models were developed as per the region-specific conditions. The most important part of such studies is the data set from previous years developed by government agencies, which proved to be the key factor in the development of any model.

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Conflicts of Interest

The authors declare no conflict of interest.

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