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REVIEW ARTICLE

Air Pollutants from Sugar Industry Chimneys: Evaluating Environmental Hazards and Global Mitigation Strategies

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ABSTRACT: This paper investigates the impact of air pollutants emitted from the chimneys of sugar industries and explores various remedial measures to reduce these emissions. Focusing on pollutants like particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and greenhouse gases, this study assesses their sources, environmental influence, and potential health risks. It examines the prevalent use of bagasse as fuel, its role in air pollution, and the associated release of toxic substances. The findings underscore the significant harm these emissions pose to human health, particularly respiratory and cardiovascular health, and address their broader implications on the economy, including tourism and agriculture. Emphasis is placed on the urgent need for these industries to transition from traditional practices to environmentally sustainable technologies, aligned with stringent global regulations. The paper argues for adopting cleaner production methods, including pollution control technologies, to limit emissions. The role of governmental policies and international cooperation is also discussed, stressing the importance of enforcing stricter environmental standards for sugar mills. This research contributes to the broader discourse on industrial pollution, offering insights that can inform future policy-making and technology adoption in sugar manufacturing.

Keywords: Press Mud, Dioxins, Greenhouse Gases, Sugar Industry, Environmental Hazard, Global Mitigation Strategies

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1. INTRODUCTION

The sugar industry is one of the oldest agro-based industries in many countries, particularly in regions with suitable climates for sugarcane cultivation, such as India, Brazil, and Thailand. In India, the journey of the sugar industry began in 1903, marking the establishment of the first sugar mill and the inception of an industry that would become vital to the nation's agrarian economy. Today, with approximately 750 operational sugar mills, the Indian sugar industry stands as the world's second-largest sugar producer, following Brazil. The scale of production not only meets domestic demand but also contributes to exports, making it a key foreign exchange earner for India [1-3].

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The sugar industry's significance in India extends beyond economic contributions; it plays a crucial role in supporting rural livelihoods. Sugarcane farming, a labor-intensive activity, provides direct employment to millions of farmers and seasonal workers. Additionally, the sector sustains a large number of ancillary businesses, from transportation to machinery manufacturing. The byproducts of sugar production, including bagasse, molasses, and press mud, have fostered the growth of related industries, such as biofuel, animal feed, and fertilizer production. These byproducts contribute to a circular economy within the sector, enhancing resource efficiency and minimizing waste. However, the environmental impact, particularly air pollution, associated with sugar production poses significant challenges that need immediate attention to ensure sustainable growth [4-6].

The sugar industry's environmental footprint largely stems from its reliance on bagasse as a primary fuel source for energy. Bagasse, the fibrous residue left after sugarcane is crushed to extract juice, is a renewable biomass material that can be used to generate steam and electricity for sugar mill operations. This practice is economically advantageous, reducing dependency on external energy sources and helping mills remain financially viable. However, the combustion of bagasse is far from environmentally benign [7].

When burned, bagasse releases several pollutants, including particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). PM is particularly harmful because it consists of tiny particles that can penetrate deep into the lungs, posing severe health risks to individuals exposed over prolonged periods. Studies have demonstrated that exposure to PM is associated with respiratory ailments, such as asthma and bronchitis, as well as cardiovascular conditions, including hypertension and stroke [7]. Additionally, SO_2 and NO_x are known to cause respiratory irritation and exacerbate conditions like chronic obstructive pulmonary disease (COPD), impacting both workers within the mill and residents in nearby communities [8]. The environmental impact of bagasse combustion extends beyond human health concerns. SO_2 and NO_x emissions are primary contributors to acid rain, which occurs when these gases react with water vapor in the atmosphere to form sulfuric and nitric acids. Acid rain has far-reaching ecological consequences, leading to soil acidification, which can harm crop yields and disrupt local ecosystems. The acidification of water bodies can also harm aquatic life, creating a ripple effect across the food chain [6].

Bagasse combustion not only generates local air pollutants but also contributes to the global issue of climate change through the release of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4). While bagasse is considered a "carbon-neutral" fuel because it is derived from plants that absorb CO_2 during growth, its combustion still releases CO_2 back into the atmosphere. Methane, though not directly emitted from bagasse combustion, is often associated with the decomposition of organic matter in sugarcane waste and the anaerobic digestion processes within sugar mills. Methane is a potent greenhouse gas, with a global warming potential 25 times greater than CO_2 over a 100-year period [9].

The sugar industry's greenhouse gas emissions are not only limited to direct emissions from combustion. The industry's overall carbon footprint includes indirect emissions associated with agricultural practices, such as the use of nitrogen-based fertilizers, which release nitrous oxide (N_2O), another potent greenhouse gas. Additionally, land-use changes for sugarcane cultivation can result in the release of CO_2 from soil and vegetation. As global temperatures continue to rise, these emissions contribute to a range of environmental issues, including extreme weather events, sea-level rise, and disruptions to biodiversity. Air pollution is a well-documented risk factor for a range of health conditions, impacting populations worldwide. In the context of the sugar industry, the air quality issues associated with bagasse combustion are particularly concerning given the large number of people who live and work in proximity to sugar mills. The primary pollutants released during bagasse combustion, including PM, SO_2, NO_x, and VOCs, have both immediate and long-term health effects. Studies indicate that exposure to fine particulate matter ($PM_{2.5}$) is linked to respiratory infections, reduced lung function, and increased mortality rates from respiratory and cardiovascular diseases [10]. SO_2, while less harmful than PM in small doses, can cause respiratory irritation and exacerbate asthma in sensitive individuals. NO_x emissions are known to contribute to the formation of ground-level ozone, which can irritate the respiratory system and lead to chronic respiratory conditions [11].

VOCs, another group of pollutants released during bagasse combustion, contribute to the formation of smog and can have both short- and long-term health effects. Short-term exposure to VOCs may cause headaches, dizziness, and eye irritation, while long-term exposure is associated with more severe health outcomes, such as liver and kidney damage and even certain cancers [4]. Given the cumulative health impacts of these pollutants, there is a pressing need for regulatory measures and cleaner technologies to mitigate emissions from sugar mills.

To address the environmental challenges associated with industrial emissions, many countries have implemented regulations that set limits on pollutant emissions from factories. In India, the Central Pollution Control Board (CPCB) has established standards for emissions from sugar mills, mandating the use of pollution control devices, such as electrostatic precipitators (ESPs) and bag filters, to reduce particulate emissions. While these regulations are a step in the right direction, their enforcement remains inconsistent, particularly in rural areas where many sugar mills are located [5]. Technological advancements offer promising solutions for reducing emissions from sugar mills. For example, gasification is an alternative to conventional combustion that converts bagasse into a combustible gas, resulting in lower emissions of PM and NO_x. Similarly, cogeneration systems that combine heat and power generation improve energy efficiency and reduce the amount of fuel required for mill operations [12]. Implementing these technologies, however, requires significant investment, which may not be feasible for all mills, particularly smaller operations.

Biotechnological approaches are also emerging as potential solutions for reducing industrial emissions. For instance, using microbial treatments to break down organic matter in sugarcane waste can reduce methane emissions. Research into biochar production from bagasse also shows promise, as biochar can sequester carbon and improve soil health when applied as a soil amendment [13]. These approaches not only offer environmental benefits but also align with sustainable agricultural practices, creating opportunities for a more circular economy within the sugar industry. The path forward for the sugar industry involves balancing economic goals with environmental responsibilities. Transitioning to sustainable production practices is essential to mitigate the environmental and health impacts of sugar production. This shift will likely require collaboration between industry stakeholders, government agencies, and research institutions to develop and implement cleaner technologies and sustainable agricultural practices.

2. MAJOR WASTES PRODUCED BY SUGAR INDUSTRY

Figure 1 shows major wastes produced are bagasse, molasses, cane tops, filler mud and smoke. Few of which are used by farmer as fertilizer. Industry itself uses bagasse as a fuel to generate electricity. About 30-40% of bagasse is productive for electricity and remaining mass is burned along with as a result not only efficiency is reduced but also smoke emission is also significant.

2.1. Bagasse

After sugar cane is processed in a sugar mill, the matted cellulose fiber waste is known as bagasse. Bagasse used to be burned in order to get rid of solid waste [4]. But with the rising costs of electricity, natural gas, and fuel oil, bagasse is now considered a fuel rather than decline. Fuels like bagasse differ in terms of composition, consistency, and heating value. In order for entire combustion take place, the carbon in bagasse changes into carbon dioxide, the hydrogen in it becomes water, and the sulfur in it becomes sulfur dioxide.

$$2\text{kg } (H_2) + 16\text{kg } (O) \rightarrow 18 \text{ Kg } (H_2O)$$

$$12\text{kg } (C) + 32\text{kg } (O_2) \rightarrow 44 \text{ Kg } (CO_2)$$

$$32\text{kg } (S) + 32\text{kg } (O_2) \rightarrow 64 \text{ Kg } (SO_2)$$

As can be seen from the chemical formulas, 1 kg of hydrogen needs 8 kg of oxygen, 1 kg of carbon needs 2.67 kg of oxygen, and 1 kg of sulfur needs 1 kg of oxygen [5]. Theoretically, 5.7 kg of bagasse is the least amount of air needed for full combustion. It shows that resource is not only harmed by combustion but also been consumed to meet high demand. The average air pollutant emission of a biomass is given in Table 1.

2.2. Press Mud

It is often known as filter cake or press cake; it is the agricultural waste obtained when cane juice is repeatedly filtered before being sent for extraction of sugar. The filters are cleaned periodically, and the waste is deposited into the yard of the mill. Nearly 3 to 4 percent of press mud is obtained when per ton of cane is crushed. At present, mills recycle this agriculture waste as manure by composting the same and supply it to the farmers in the area. Press mud from sugarcane byproducts has the potential to produce 460,000 tons of compressed biogas (CBG), worth Rs 2,484 crore. Large volumes of press mud are released by the sugarcane industry, and getting rid of this waste is a big problem [7]. Millions of tons of nutrients are lost and wasted when press mud is burned in brick kilns, which eventually deteriorates the ecosystem.

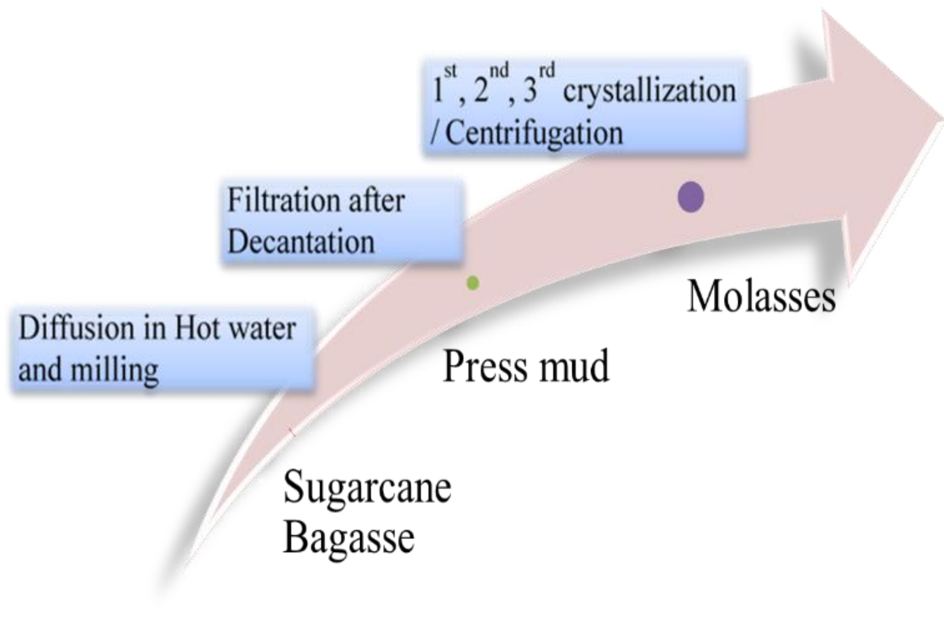

Fig. 1. Flow chart showcasing by-products (on right side) produced during different operation.

Table 1. Average air pollutant emission of a biomass (bagasse).

S. No.	Description of Air pollutants	Quantity in kt (kilo Tonnes)
1.	SO_2	40.5
2.	NO_X	79.8
3.	OC (organic carbon)	4.2
4.	EC (elemental carbon)	1.0
5.	NMVOC (non-methane volatile organic compounds)	31.7
6.	Traces of metals (Pb ,As, Cr, etc)	0.11

2.3. Molasses

A viscous leftovers molasses is mostly made when sugarcane or sugar beet juice is refined to make sugar. The amount of sugar, the extraction process, and the age of the plant all vary in molasses. A significant amount of complicated distillery effluent is released during the manufacturing of ethanol. 13 L of stillage is produced for every 1 L of cane molasses-based ethanol that is produced, using 4-5 kg of molasses as feed. Over 30,000 m^3 of drinkable alcohol are thought to be produced on an average scale [8]. Therefore, the impact of the yearly discharge of almost 260 million liters of stillage on the environment and the best treatment options to reveal the sustainability of the industry are the areas of concern [9]. Indeed, the chemical oxygen demand (COD) of the stillage after anaerobic digestion (AD) stays between 21,000 and 50,000 mg/l, which is considerably greater than the Central Pollution Control Board's 250 mg/l COD discharge limits. A few inexpensive and ecologically sustainable bioprocesses have been developed for the microbial synthesis of value-added bio-products from molasses. Through microbial conversion, a growing amount of biofuels, polysaccharides, oligosaccharides, organic acids, and enzymes have been created from the molasses during the past ten years. These products have several significant uses in the food, energy, and medicinal industries.

3. COMPOSITION OF POLLUTANTS THROUGH SUGAR INDUSTRY

Air is the mixture of gases .it involves various gases as Nitrogen 78%, Oxygen 21%, Carbon dioxide 0.03% and etc. Continuous supply of fresh air is very essential for breathing in most of living organisms. Polluted air is not suitable for living organisms and it may lead to difficulties in breathing and spread of various diseases and illness. Sugar industry is one of the most common agro-based industry. Sugar industry releases various gases and pollutants into environment (Figure 2) as follows: Carbon monoxide, sulfur dioxide, nitrogen oxides, volatile organic compounds, particulate matter, and greenhouse gases are only a few of the pollutants that the sugar industry releases into the environment.

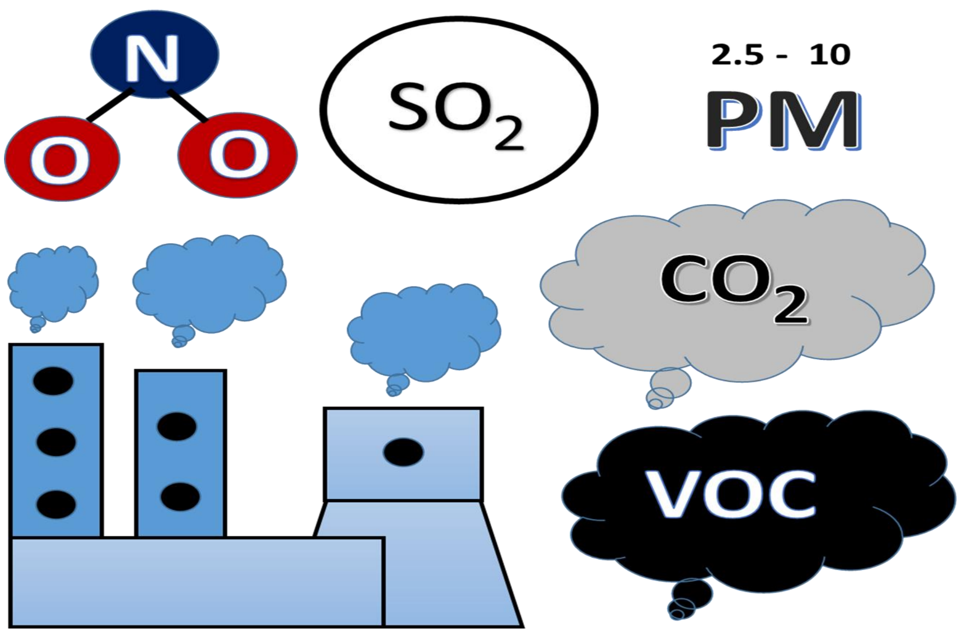

Fig. 2. Major pollutants emitted by Sugar Industry.

3.1. Particulate matter (PM)

Small particles that can cause respiratory issues and other health problems. Animals and humans alike may experience a range of health issues as a result of breathing particulate matter (PM2.5–PM10), such as asthma, lung cancer, low birth weight, early delivery, and birth abnormalities [10]. PMs are tiny substances that are either solid or liquid (aerosol) and bimolecular in nature. They are responsible for processes such as cell division, morphogenesis, and development. In addition to being a major contributor to the premature deaths of the human population, particulate matter and hazardous gases can alter the atmosphere and induce a variety of diseases, illnesses, or allergies. Air pollution also affects other life processes, demonstrating that the additionally, it can have an impact on food crops and animals. PM presents a variety of difficulties that impact regulatory initiatives, the environment, and human health. It is challenging to evaluate overall health risks because the effects of PM can differ greatly from person to person and are impacted by age, pre-existing medical disorders, and hereditary variables. As awareness of the negative health effects increases, countries are expected to enact stricter air quality regulations, striving for lower acceptable PM levels. [11].

3.2. Carbon monoxide (CO)

A colorless, odorless gas that can cause headache, dizziness and nausea. The quantity of oxygen that can be carried by the bloodstream to vital organs like the heart and brain is decreased while breathing air that has a high CO concentration [12]. Both the environment and human health are impacted by tropospheric chemistry, which is influenced by CO. Although it can potentially create health problems, this gas has detrimental effects on humans and is deadly at large doses (>1000 ppm). Lesser concentrations of affections. The production of tropospheric O_3 and CO_2 can be triggered by CO. A higher proportion of CO can cause smog and have an impact on air quality and visibility [13].

3.3. Volatile Organic Compounds (VOCs)

Volatile Organic Compounds (VOCs) represent a diverse group of organic chemicals characterized by their ability to evaporate easily at room temperature. This property makes them prevalent in various indoor environments, primarily due to their presence in common household products such as paints, cleaning agents, adhesives, and building materials. When released into the atmosphere, VOCs can react with nitrogen oxides (NO_x) in the presence of sunlight to form ground-level ozone, a significant component of smog. This chemical reaction not only contributes to outdoor air pollution but also adversely affects indoor air quality, posing various health risks to occupants.

VOCs can cause a range of health effects, particularly when individuals are exposed to them in significant concentrations over time. Short-term exposure may lead to symptoms such as irritation of the eyes, nose, and throat, headaches, dizziness, and exacerbation of asthma symptoms. Long-term exposure to certain VOCs has been associated with more severe health issues, including liver damage, kidney damage, and even cancer, depending on the specific compound and duration of exposure [14]. The World Health Organization (WHO) has highlighted the need for stringent monitoring of VOC levels, particularly in occupational settings where exposure may be higher.

Accurately assessing atmospheric VOC exposure can be challenging due to several factors, including the variability of respiratory coefficients. These coefficients can differ dramatically based on individual susceptibility, the specific VOCs involved, and the levels of exposure experienced. This variability can lead to significant uncertainties in understanding the actual risk posed by VOC exposure [14]. Therefore, comprehensive studies that incorporate various exposure scenarios are essential for a more accurate assessment of health risks associated with VOCs.

In a recent analysis of indoor air quality, the planned limit for VOCs was set at 300 $\mu g/m^3$. However, measurements taken the day after the delivery of new furniture and materials showed a total concentration of VOCs reaching around 14 mg/m^3, significantly exceeding the proposed limit. This finding underscores the potential for indoor environments to harbor hazardous levels of VOCs, particularly in newly renovated or constructed spaces. Prolonged exposure to such high concentrations can lead to serious health implications for residents, particularly vulnerable populations such as children, the elderly, and those with pre-existing respiratory conditions.

Moreover, research has indicated that personal exposure to VOCs is not limited to indoor environments. In fact, studies show that between 10% and 20% of an individual's overall exposure to VOCs can occur during commuting from home to work [15]. This exposure may arise from a combination of factors, including vehicle emissions, off-gassing from materials within the vehicle, and the presence of VOCs in the ambient air along commuting routes. Consequently, it is essential to consider the full spectrum of VOC exposure sources, including both indoor and outdoor environments, to develop effective strategies for reducing exposure and improving public health outcomes. VOCs are a significant class of compounds with substantial implications for human health and indoor air quality. Understanding their sources, health effects, and exposure dynamics is crucial for formulating effective guidelines and regulations to mitigate their risks. As urbanization continues and indoor environments become more complex, ongoing research and proactive measures will be essential to safeguard public health from the harmful effects of VOCs.

3.4. Sulfur dioxide (SO_2)

A gas that can cause respiratory problems and contribute to acid rain. The most corrosive gas in the atmosphere is known to be sulfur dioxide, and the presence of additional pollutants may make it more hostile [16]. The global climate is directly impacted by the sulfate aerosols that are produced. It has been proposed that geoengineering, or the intentional injection of SO into the stratosphere, can reduce anthropogenic climate change by raising Earth's albedo. However, adverse impacts like ozone layer loss may result from the artificial injection [17].

3.5. Nitrogen dioxide (NO_2)

Gases that can cause respiratory issues and contributor to ground level ozone formation. As one of the air pollutants that is routinely monitored, nitrogen dioxide (NO_2) has greater regional heterogeneity since it has a shorter atmospheric lifetime than related air pollutants like fine particulate matter (PM 2.5) [18-20]. Among the several nitrogen oxides, NO_2 is one of the most prevalent air pollutants and hazardous gases. There are many different sources of it. In addition to naturally occurring NO_2, human manufacturing activities has contributed to the atmosphere's highest concentration. In addition to causing acid rain, accelerating global warming, and weakening the ozone layer, nitrogen dioxide also harms the respiratory system and may even be fatal [21].

3.6. Carbon dioxide (CO_2)

A greenhouse gas that contributes to climate change and various health issues. Global warming is the term used to describe the rise in Earth's temperature caused by an increase in carbon dioxide levels. Because of this, carbon dioxide is regarded as a pollutant [22]. Continuous increases in CO_2 emissions into the atmosphere have accelerated the effects of global warming and extreme weather occurrences. The global average temperature is expected to rise to 6.1 °C at the end of the 21st century if present trends continue, since the atmospheric concentration of CO_2 is expected to reach 530-980 ppm by that time, about double the current level of 410 ppm [23].

3.7. Polycyclic Aromatic Hydrocarbons (PAHs)

Toxic chemicals that can cause cancer and other health problems. The broad class of chemical molecules known as polycyclic aromatic hydrocarbons (PAHs) is composed of two to seven benzene rings. In humans, PAHs lead to various consequences such as respiratory issues and an elevated risk of cancer. Food, industrial pollutants, and other sources of mobile and fixed air pollution (PAHs) are the most significant [24-25]. The US Environmental Protection Agency (EPA) has designated 18 PAHs as priority pollutants to safeguard human health due to their carcinogenic and mutagenic properties. Numerous recent research on PAHs have concentrated on epidemiology, DNA damage assessments, and atmospheric emissions [26].

3.8. Dioxins and Furans

Highly toxic chemicals that can cause cancer and other health issues. Dioxins and furans, also known as just "dioxins", any technique that involves high temperatures and any kind of chlorine can produce dioxins [27]. Dioxin-like polychlorinated biphenyls (PCDD/Fs and dl-PCBs; "dioxins"), polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans are common environmental pollutants with half-lives in the environment and human body that are estimated in decades. With the implementation of control measures, exposure levels are typically declining over time in the majority of nations. Serious health consequences, such as immune system impairment, problems with reproduction, and an elevated risk of cancer, can result from exposure to dioxins and furans. This may result in air quality-related public health issues. Many nations have put laws in place to restrict emissions of furans and dioxins because of their toxicity. This involves regulating industrial emissions and keeping an eye on the quality of the air [28].

3.9. Greenhouse gases

Gases like methane and nitrous oxide that contributes to climate changes. Because these gases have a positive radiative forcing effect, they directly contribute to climate change. The term 'F-gases' refers to the combination of HFCs, PFCs, SF6, and NF3. The inventory includes nitrogen oxides, carbon monoxide, and non-methane volatile organic compounds (NMVOCs) since they can raise tropospheric ozone concentrations, which in turn raises radiative forcing (atmospheric warming) [29].

4. ADVERSE EFFECT OF AIR POLLUTANTS

4.1. HEALTH EFFECT

4.1.1. Respiratory Problems

Air pollution can permanently injure the lungs, raising the chance of acquiring chronic respiratory diseases such as asthma, Chronic Obstructive Pulmonary Disease (COPD), and lung cancer.

4.1.2. Cardiovascular Diseases (CVDs)

Due to air pollution chronic exposure of poor-quality air can be increases that risks to the heart attack, strokes and other cardiovascular diseases [30] as shown in Figure 3. Researchers worldwide have shown a great deal of interest in the connection between air pollution and cardiovascular illnesses. An overview of recent research on the link between air pollution and CVDs was provided by this study using bibliometric analysis, which also provided a thorough review of worldwide research trends in this field. Despite the well-established negative impact of air pollution on respiratory conditions, it is important to emphasize that 50% of deaths from air pollution are caused by CVDs. Additionally, strong worldwide data has unequivocally shown that human exposure to air pollutants such PM2.5, PM10, ozone (O_3), and nitrogen dioxide (NO_2) is responsible for about 20% of CVD deaths [31].

4.1.3. Birth Defects and Infant Mortality

Air pollution has devastating effects on fetal development and infant health. The developing lungs and brains of infants and children make them more susceptible to the harmful effects of air pollution. Among all risks global morbidity and mortality ranks the 4th position. There may be a higher chance of congenital defects in the offspring of pregnant women exposed to elevated levels of air pollutants. At critical junctures, pollutants can disrupt embryonic development. Air pollutant also causes oxidative stress which leads to damage of cells, defects in fetal growth. Poor air quality enhances the respiratory disorders in infant. Also air pollutant are responsible for low birth weight, premature birth [32].

4.1.4. Neurological Damage

Beyond its direct effect on respiratory health, air pollution has a major global impact on neurological and psychiatric illnesses. Next to respiratory health, air pollution has a substantial impact on neurological and psychological conditions, making it a serious worldwide concern. SO_2 NO_2, and PM (< 2.5 µm) exposure have been linked in recent research to increased risks of dementia, Alzheimer's disease, schizophrenia, Attention deficit hyperactivity disorder (ADHD), stroke, Parkinson's disease, and multiple sclerosis. The breakdown of the blood-brain barrier, oxidative stress, microglial activation, cerebrovascular dysfunction, and neuroinflammation are examples of mechanistic pathways. Urban dwellers, especially men, middle-aged people, and married people, are more vulnerable to the negative effects of air pollution on their mental health, according to epidemiological research [33].

4.1.5. Cancer

Human who are exposed to outdoor air polluted, such as PM 2.5, have a higher risk of developing cancer due to increased genetic damage, which includes cytogenic abnormalities, altered gene expression, and somatic and germ cell mutation [34]. Polluted air consists of toxic chemicals like polycyclic aromatic compounds which are cancer causing.

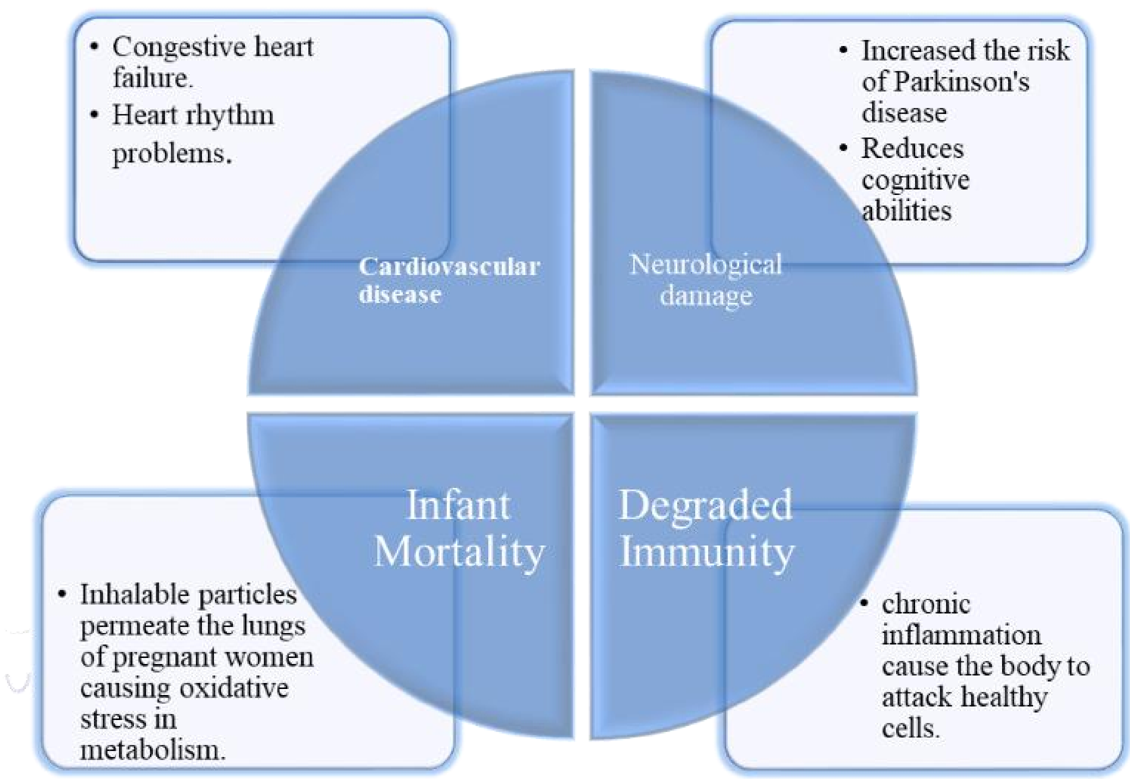

Fig. 3. Highlights various issues that are confronted by human.

Fig. 4. Showcasing the wide range of adverse effects confronted by environment.

Critical environmental exposures that may negatively impact ovarian cancer (OC) survival include ambient air pollution, particularly PM with a diameter of 2.5 microns. Notably, recent research has established links between exposure to various airborne contaminants and chronic illnesses by using a weighted air pollution score (APS) to quantify the cumulative health harms linked to such exposure. Nevertheless, no epidemiological research has looked at the possible links between OC survival and APS [35].

4.1.6. Effect on Nervous System

Globally, nervous system diseases are one of the leading causes of death. This condition is linked with air pollution by the growing scientific evidences. The vascular tone, endothelial function and thrombosis are directly affected by the air pollutants. The association between air pollution exposure and increase risk of cerebrovascular disease is further supported by the systematic reviews and Meta – analyses [36]. Long before 2002, the central nervous system was thought to be the main organ that environmental pollutants would impair. There is substantial evidence that environmental pollution may have neurotoxic effects on the nervous system. People's lives have always been intimately linked to environmental contaminants. Between 9 million and 12.6 million deaths are thought to be brought on by pollution, including 1.8 million deaths from water pollution, 0.42 million deaths from consuming tainted food, and 7 million premature deaths from air pollution. The hysteresis and concealability of soil contamination are significant, and it frequently transfers toxicity to food, water, or air, resulting in mortality. As seen by the high number, avoidable environmental issues have had a permanent effect on people's lives [37].

4.2. ENVIRONMENTAL EFFECT

4.2.1. Acid Rain

Gases like nitrogen oxide, Sulphur oxide etc. are responsible for the acid rain (Figure 4). Polluted air releasing from the sugar industry is rich with such gases. The gases from this pollution reacts with the oxygen, other gases and water to become sulfuric and nitric acid and increase the pH of the water and this tends to increase in acidity of the water. The pH of acid-impacted rain water is generally below 4.5 on the pH scale. Even while emissions of CO_2 continue to rise. Global acid deposition has decreased by more than 50% since the 1990s, but China still has the third-highest concentration of acid deposition in the world, behind North America and Europe. Its regional acid deposition is also at a high level, and environmental pressure should not be disregarded. It is anticipated that the degree of its harmfulness will continue to rise before the carbon peak is reached. It is anticipated that the damage would keep growing until the carbon peak is reached [38].

4.2.2. Increase in ground-level Ozone

Ozone layer protects the earth from the sun's harmful radiation. But the ground level ozone harms the living organisms and plants. Ground level ozone is the air pollutant. Organic volatile compounds and nitrogen oxides react with each other in presence of hot temperature and sunlight and forms ozone. Breathing ground level ozone is very harmful, it can reduce lungs functioning and damage lungs tissues permanently.

4.2.3. Eutrophication

Due to excessive nutrients phytoplankton blooms are forms this is refer as eutrophication. Nitrogen and Phosphorous are the significant factors which affects the eutrophication. Excessive amount of eutrophication stimulates harmful algal blooms, depleting oxygen water bodies [39]. Freshwater habitats have suffered greatly from sediment contamination brought on by eutrophication. Increased nitrogen (N) and phosphorus (P) input from fast urbanization and agricultural activities is what causes eutrophication. N and P sources fall into two categories: industrial effluent and external pollution, which primarily comes from the agricultural sector. Sediment-released nutrients, however, may contribute to interior contamination. (a) increased biomass production in phytoplankton/macrophyte, (b) increased cyanobacterial species, (c) loss of coral reef communities, (d) increased fish mortality, (e) oxygen depletion, (f) poor water quality and low aesthetic values of water bodies are adverse effects of eutrophication [40].

4.2.4. Climate change

Air pollution contributes in the rising temperature due to emission of carbon dioxide. This increases global warming, altering ecosystem, see levels and weather patterns. According to the National Oceanic and Atmospheric Administration (NOAA), Annual Climate Report 2023 an average rate of ocean temperature and combined land increased at 0.06 °C per decade since 1850. The warming rate since 1982 has least three times as fast with an average rate of 0.20% per decade [41].

4.2.5. Loss of Biodiversity

Air pollution occurring by the industries effects on the health of the organisms. Many organisms have their specific type of habitat, due to climate change and various spreading diseases organisms' fails to survive. Due to the unsuitable environmental changes like temperature, humidity, acidity etc., many of the rare organisms get dead and the loss of biodiversity occurs. As species and habitat loss, rise biodiversity loss and rises the possibility of new infectious diseases outbreaks. Part of the reason for the swift decrease in biodiversity is pollution and climate change [42].

4.2.6. Risk of wildfire

Due to global warming risk of wildfire is increased. Temperature of the environment is increased as the result, trees in forest get fired easily in summer temperature. In Australia, Brazil, and the United States more than 70,000 wildfires occurs per year [43]. The radiative forcing on the surface is caused by atmospheric aerosols, which have an impact on the global climate as well as local and regional weather patterns. Because of their dispersion and absorptive qualities, or "direct effect," aerosol particles are to blame for a variety of environmental impacts, including significantly contribute to the issue of visibility, and they can also have a major effect on UV radiation and boundary layer photochemistry [44].

4.2.7. Increase in the risk of natural disaster

Polluted air can adversely effect on natural disasters, making them more frequent and long lasting. Air pollution can lead to land degradation, increasing the risk of landslides.

4.3. ECONOMIC EFFECT

4.3.1. Infrastructure damage, Health care cost and Productivity loss

Some air polluting agents affects on the infrastructure components like buildings. Sulfur dioxide (SO_2) and interaction with nitrogen dioxide (NO_2) and ozone (O_3) damage the materials when in contact with water [45]. Example, color of Taj Mahal, India is faded due to polluted air. Air pollution increased the spread of diseases due to this the expenses on the health care, medicines and other hospitalizations is also increased. The ground –level Ozone due to pollution damages the respiratory system and cardiovascular system and it tends to loss the labor productivity. Figure 5 highlights different sectors of economy affected by untreated air pollutants.

4.3.2. Agricultural Impacts

Air pollution affect agriculture directly as well as indirectly. Air pollution influences agricultural productivity in three major ways as Harm creature's biological processes like growth and development. Significantly hurts the soil and water quality. Decreases labor's ability of working by damaging the health [46]. GDP reduction (Gross Domestic Product): Air pollution can lead to the reduction in GDP. Increase urban heat-related health risks because cities collect and hold more sunlight during the day and release it at night. When temperatures in metropolitan regions are higher than those in rural areas, the metropolitan Heat Island effect occurs [47]. This effect gains potential to reduce the productivity of agricultural land leading to loss of crops.

4.3.3. Tourism and recreation impact

Air pollution effects on natural environment, traffic safety and human health which inhibit the tourism. Tourism demand and tourism competitiveness is also affected by the environmental quality [48]. The tourism industry's environmental responsibility is essential to economic prosperity. The service sector tourist industry is being closely examined because of its significant environmental impact. The desire to escape the urban environment and the need to reinforce personal identities in reaction to growing urbanization can be seen as the root causes of rural tourism. The effects of tourism-related businesses on the environment have not yet been taken into account. Energy usage in the tourism and hospitality industries pollutes the environment. Energy is needed for daily activities and transportation [5, 49].

4.4. DEPLETION OF NATURAL RESOURCES

When a resource is used up more quickly than it can be regenerated, it is said to be depleted (Figure 6). Renewable and non-renewable resources are the two main categories of natural resources. Resource depletion occurs when either of these types of resources are used more than they can be replaced.

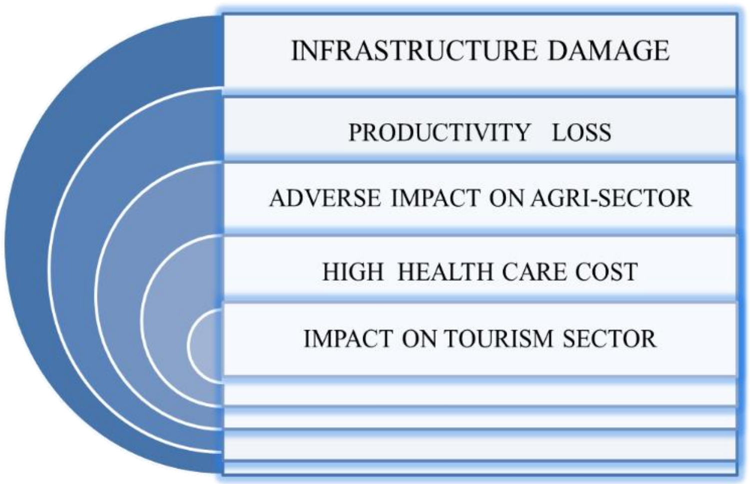

Fig. 5. Highlights the different sectors of economy affected by untreated air pollutants.

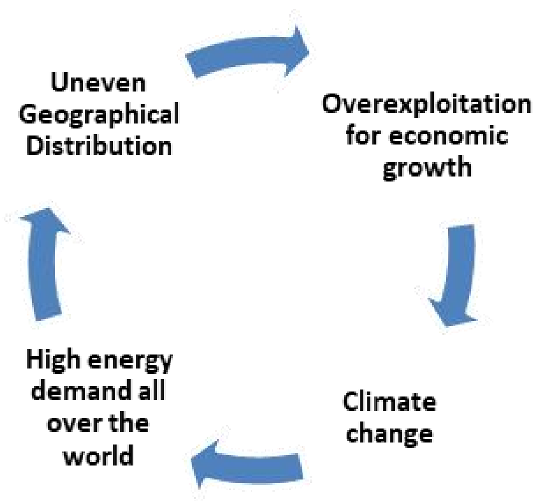

Fig. 6. Depletion of Natural Resources due to unsustainable activities.

A resource's worth is directly correlated with both its cost of extraction and its availability in the natural world. A resource's value rises in direct proportion to its depletion [50]. Air is one of so called natural resources. In Sugar Industry Drum dryer with vertical fluidised-bed cooler & air conditioner is used to dry sticky and highly viscous liquids and pastes. Even further the air consumed is heated up between 70° - 80° C for drying purpose [51]. Which is later set free to enter the atmosphere. The above data is just an overview of sugar industry, considering it at level field so as to not make one sector responsible for air pollution, if we analyze performance of other industries the statistics will get ten times higher. The late 19th century, which marked the beginning of the industrial revolution, saw an increase in the Earth's average temperature of around 0.3 degrees Celsius (0.5 degrees Fahrenheit). It linked this warming to the rise in atmospheric carbon dioxide resulting from the majority of industrial operations burning fossil fuels for energy [52].

5. REMEDIES

As we have previously discussed, air pollution has a disastrous effect on the environment, the economy, human health, and natural resources. Essential and practical solutions that address the underlying causes of air pollution and support sustainable economic growth must be put into place in order to mitigate these effects. In this study, to lessen the air pollution the remedies like set emission standards, carbon pricing, clean energy subsidies and green infrastructure investment, air quality monitoring, research and development funding have been discussed in details. The Figure 7 depicts the remedies to curb the air pollutant.

5.1. Set emission standards

Impose stringent emissions regulations on industry. Establishing standards Emission refers to setting a limit or threshold for the quantity of pollutants that can be discharged into the atmosphere from a particular source, such as a power plant or factories. Standards can be of the following types:

(i) Technology-based standards: these call for the use of particular technology to decrease emissions [53].
(ii) Performance-based standards: establish precise emission caps for different sources
(iii) Prescriptive standards: Identify precise emission limits, specific to individual sources.

5.2. Carbon pricing

One of the most well-liked policies to cut greenhouse gas emissions is carbon pricing. In academic research and policy circles, carbon pricing has garnered significant backing as an economically viable approach to reduce greenhouse gas emissions. Since 2005, the European Union (EU) has implemented an emissions trading scheme for stationary sources from the electricity sector and some energy-intensive industries in order to put a price on carbon [54]. Figure 8 illustrates how carbon credits operate globally to lower carbon emissions.

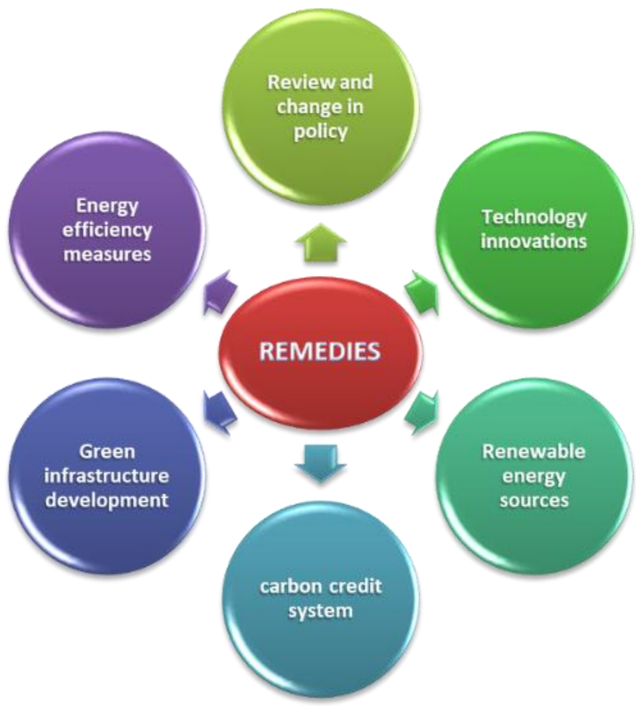

Fig. 7. Remedies to curb the air pollutant and ongoing ill effects.

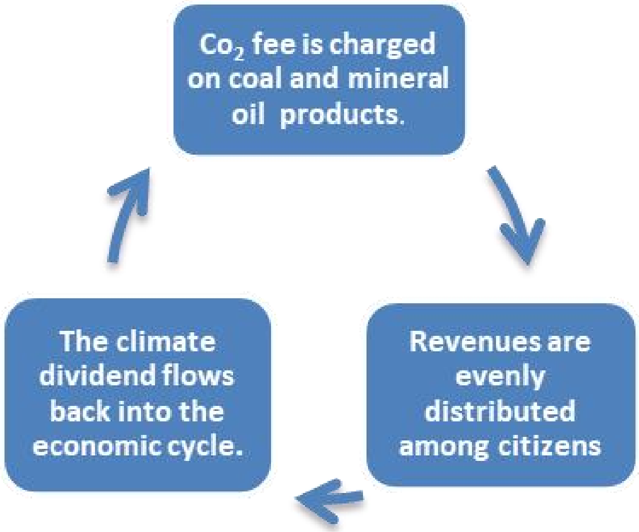

Fig. 8. Working of carbon credit at global level, leading to reduced carbon emission.

5.3. Clean energy subsidies

Provides tax breaks and incentives to promote the development and use of renewable energy sources, such as solar and wind power. Residents in locations with greater pollution levels rely heavily on the subsidies offered by the local government. Generally, 50%, 60%, 70%, or 100% of the equipment expenses are covered by local government subsidies [55]. By combining a carbon tax & clean subsidies, and machine subsidies, the socially optimum allocation may be put into practice. Because services and energy complement each other, long-term allocations stabilize and the clean and services sectors develop at the same rate during a clean transition. Research in the clean industry is at its best, and numerical models indicate a time of high production factor utilization [56].

5.4. Green infrastructure investment

Invest in green infrastructure, such as parks, green roofs, and green spaces, to improve air quality and mitigate the effect of the urban heat island (Figure 9). Enhancing social cohesion among inhabitants, lessening the consequences of urban heat islands, and lessening the effects of surface flooding. In addition to increasing public and practitioner understanding of the natural approach, green infrastructure (GI) has the potential to provide (re-)integration of (semi-)natural elements to produce healthier, more climate-resilient, and pleasurable spaces for urban dwellers. Urban planners are finding that (retro) fitting natural components in crowded surroundings is a viable way to foresee and reduce unfavorable outcomes [57].

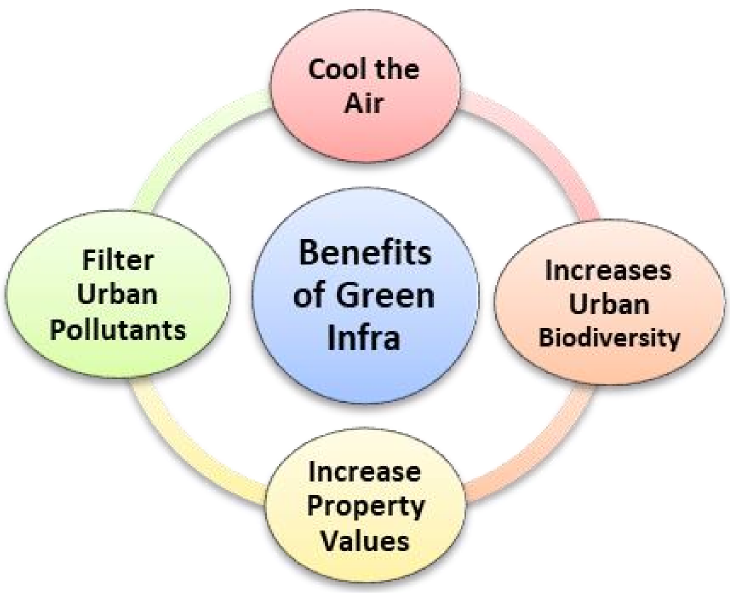

Fig. 9. Enhancing air quality through Green Infrastructure

5.5. Air Quality Monitoring

Create a network for monitoring air quality in order to keep tabs on pollution levels and influence policy choices. Putting measures for improving air quality and reducing carbon emissions into two categories: static and dynamic policies; considering how policies interact and complement one another; and including data on respiratory illnesses to further investigate the effects of policies. The theoretical basis for creating environmental policies that are more detailed and exact is provided by this procedure. Effectively handling nonlinearity and dynamic uncertainty can be achieved by combining causal network models and Gaussian process regression. Improved explanatory power and precision of the model can lead to new opportunities for policy assessment and optimization by revealing policy interactions and causal impacts through network topology [58].

5.6. Research and development funding

Various funding agencies are providing the funding for the study and advancement of energy-efficient, clean energy, and pollution-reduction technologies to reduce the air pollution. Over the past 50 years, funding for research and development in higher education has been essential to the expansion of social and economic innovation [59]. Environmental Protection Agency (EPA), National Institutes of Health (NIH), Department of Energy (DOE) provides funds for programs that attempt to improve air quality and reduce pollution, Support research on its effects and potential mitigation techniques and for clean energy technologies [60].

6. FUTURE PERSPECTIVES

6.1. Technology Innovations

The creation of new technology, procedures, and goods that lessen resource and energy consumption as well as environmental pollution is referred to as "green innovation." Thus, it stands to reason that green innovation can lower urban air pollution, a conclusion that is corroborated by the body of research in this field. Many countries are taking initiatives to install hydrogen valley as given in Table 2. Two more sets of analyses were conducted once it was determined that there was evidence that pollution prevention innovation improved the financial performance of businesses in the future. There are two fundamental methods by which innovations in pollution avoidance can impact the financial performance of businesses in the future [61]. One possible mechanism is that businesses that innovate in pollution prevention can draw in eco-aware customers, increasing the demand for their goods and, thus, driving up sales growth. The other is that by increasing resource productivity these innovations enable businesses to lower manufacturing costs, resulting in increased gross margins and operational effectiveness. Proof in favor of both mechanisms. More specifically, a company's future sales growth, gross margin, and operational efficiency are all positively correlated with the value of its pollution avoidance patents. Secondly, we discover that the correlation that is positive between pollution, preventive innovation and future financial success is stronger for businesses in sectors that rely more heavily on energy inputs and for businesses that have historically produced more pollution. These findings align with the idea that innovations in pollution prevention enable businesses to use energy and resources more effectively [62].

6.2. Renewable energy sources

6.2.1. Solar energy

This energy is produced by the sun’s rays. Concentrated solar energy may produce heat without releasing any hazardous substances like carbon dioxide, even at temperatures as high as 3000 °C. Furthermore, solar energy can be used in isolated locations without access to the electrical grid and is essentially free [63]. In order to achieve global carbon neutrality, industrial decarbonization need the low-carbon supply of large amounts of process heat. When it comes to heat-driven industrial processes, solar energy is thought to be one of the most promising substitutes for fossil fuels. Nearly three-quarters of the energy needed for industry is utilized as process heat at various temperatures, with around 30% of all industrial process heat needed at temperatures lower than 150 °C. Using solar-thermal conversion devices, direct thermal utilization transforms solar energy into the thermal energy of a working fluid. It has the benefit of being easy to use and having a high energy efficiency because it only needs one energy conversion step, as opposed to thermochemical energy storage and electricity production [64].

6.2.2. Wind energy

Energy produced by the wind and transformed into electrical power by wind turbines. Numerous problems could be resolved by wind energy. As a renewable energy source, reducing reliance on distant power networks promotes environmental sustainability, boosts energy security, and offers an alternative to energy independence. Additionally, the growth of wind energy in these areas boosts local economies and opens up job opportunities in manufacturing, building, maintenance, and operation. Through land leasing agreements, wind farms may give land owners additional cash [65].

6.2.3. Hydrothermal energy

This energy is generated from the movement of water in rivers, oceans or tidal currents, using tidal power turbines or hydroelectric power plants (Figure 10). Maintaining the continuity of electrical energy supply to all users requires the requirement of an alternative energy-producing source to meet the load demand throughout the day. In order to provide customers with energy at the greatest price, hydro plants are connected to thermal generating unit (TGU) to build a hydrothermal system. Water is the input and there are no operating costs associated with producing energy in a hydro plant. Plants that generate hydropower do not emit any emissions. Water resource constraints for hydropower facilities and the growing demand for electricity from daily activities, industry, and agriculture make hydrothermal systems uncompetitive [66].

6.2.4. Geothermal energy

Energy produced by the heat of the earth's core and used to produce electricity and provide heating and cooling. Despite being a typically cost-effective energy source, geothermal energy is site-specific and does not, by itself, offer enough financial incentives to draw in manufacturing or process industries. Worldwide interest in investing in energy-intensive sectors has decreased due to global economic slowdowns and structural issues in many process industries following the energy crises of the 1970s. To support Greenfield investments, another locally accessible manufacturing element that provides further competitive advantage is typically needed [67].

6.2.5. Biomass energy

Energy produced from the organic matter such as crops, wood, waste and through combustion, anaerobic digestion or gasification. One potential remedy for the environmental contamination linked to conventional carbon aerogel manufacturing is the synthesis of carbon aerogel from biomass.

Table 2. Initiatives by various countries to install Hydrogen Valley along to meet growing hydrogen demand in various Industrial, Residential and transportation sector [60].

Country	Project name	Final Production of H_2 (tonnes / annum)
France	Normady Hydrogen	33000
Chile	Green Hydrogen Magallanes	980000
Finland	Naantali Green Hydrogen and Ammonia plant	11000
Ukraine	H_2U Hydrogen Valley	210000
Spain	Basque Hydrogen Corridor BH_2C	39679
Portugal	Averio Green H_2 Valley	5700

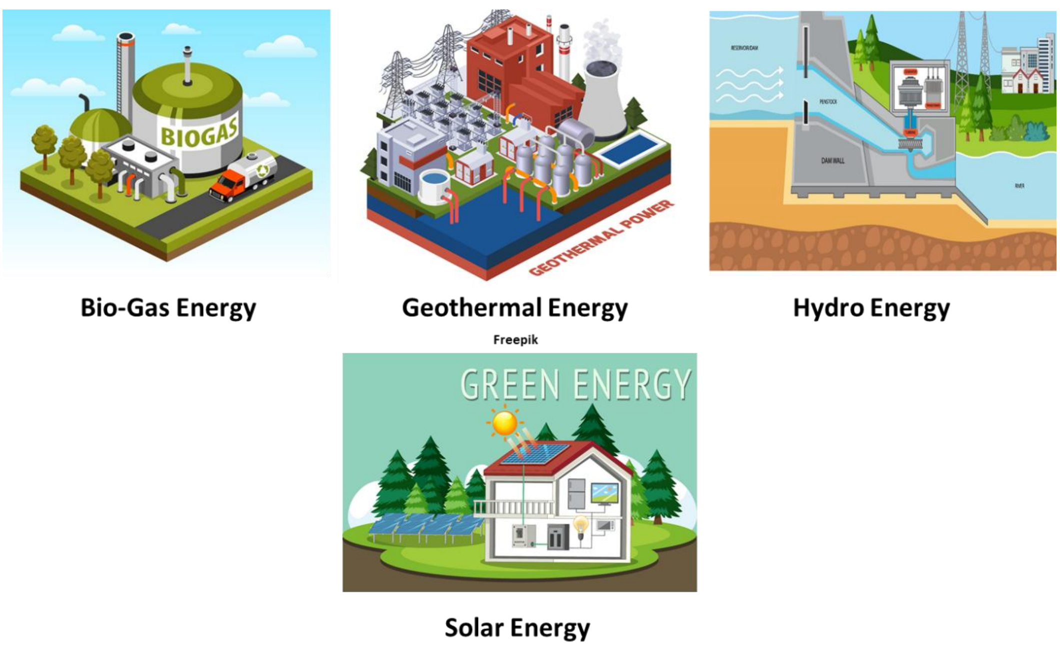

Fig. 10. Key areas to switch from conventional energy sources to renewable energy sources.

Additionally, turning agricultural solid waste, such straw, into biomass aerogel increases the sustainability and environmental value of biomass aerogels by turning waste into useful resources. Utilizing waste may be crucial to both energy reduction and environmental preservation. The main steps in the synthesis of carbon aerogels are carbonization, drying, and gelation. Promising uses for biomass carbon gels include catalysis, batteries, and supercapacitors. The cost-effectiveness of precursors, their environmental sustainability, and the higher performance of final products are the main reasons for the current emphasis on creating aerogels from sustainable biomass resources. Converting biomass into valuable energy storage materials is a practical way to advance renewable energy projects [68].

6.3. Cleaner Production Techniques

Future research must prioritize the exploration of cleaner production methodologies aimed at reducing emissions directly at their source within the sugar industry. By innovating the processing of sugarcane, the reliance on high-energy combustion stages can be significantly minimized, which will lead to a substantial decrease in overall pollutant output. This innovation can include refining mechanical extraction and processing techniques to enhance efficiency while lowering energy consumption. Additionally, advancements in bioengineering could play a critical role in developing sugarcane varieties that are inherently more sustainable, requiring less processing energy and yielding higher biomass. These strategies not only improve environmental outcomes but also enhance the economic viability of sugar production, aligning with global sustainability goals.

6.4. Policy and Regulation

Policy frameworks at both national and international levels should be strengthened to enforce air quality standards for industrial emissions. These policies should promote sustainable production practices and provide incentives for industries adopting pollution-reducing technologies. Future research should evaluate the effectiveness of existing policies and identify areas for improvement, particularly in developing countries with high sugar production.

6.5. Public Awareness and Stakeholder Engagement

Educating stakeholders, including industry players, workers, and local communities, about the environmental and health risks of air pollution is critical. Programs that highlight the importance of cleaner production and the health benefits of reduced pollution can help drive demand for change. Engaging with communities can also lead to collaborative efforts in monitoring emissions and advocating for better industrial practices.

6.6. Life Cycle Assessment (LCA)

A comprehensive life cycle assessment of the sugar production process, from sugarcane cultivation to waste disposal, could provide valuable insights into areas where emissions can be minimized. Such studies can help the industry identify the most pollutant-intensive stages of production and implement targeted strategies for emission reduction.

6.7. Research and Development in Biofuels

Research and development in biofuels, particularly focusing on molasses, a byproduct of sugar production, offers significant opportunities for the sugar industry to positively impact the renewable energy sector. By converting molasses into bioethanol, sugar mills can reduce waste while generating an alternative energy source that contributes to the biofuel market. Future studies should not only investigate efficient conversion technologies but also evaluate the environmental implications of these processes, particularly concerning air quality and emissions. This transition towards bioethanol production can enhance sustainability, reduce reliance on fossil fuels, and create a supplementary revenue stream for sugar industries, promoting a circular economy.

7. CONCLUSION

The investigation into the environmental and health impacts of air pollutants from sugar industry emissions highlights critical concerns and the need for substantial change within the sector. Emissions from the combustion of bagasse and fossil fuels have been found to produce a variety of harmful pollutants, including PM, SO_2, and NO_x, that threaten public health and contribute to global warming. Long-term exposure to these pollutants is associated with a rise in chronic respiratory and cardiovascular diseases and potentially exacerbates neurological disorders. The trajectory of current emission practices, if unchanged, will further stress ecological balance, degrade soil and water quality, and increase the economic burden on health systems. Additionally, emissions affect the agricultural productivity and tourism industries, underscoring the interconnectedness of environmental health and economic stability. The need for technological advancement in pollution control and cleaner production processes in the sugar industry is pressing. Existing sustainable alternatives and pollution abatement technologies, such as scrubbers, electrostatic precipitators, and gas filters, should be integrated into the operations of sugar mills. The transition towards green technologies, coupled with stringent policy frameworks and enforcement, can lead to improved environmental outcomes. Governments and international regulatory bodies must act with urgency, fostering collaborations that hold industries accountable and encourage environmentally responsible practices. Addressing sugar industry emissions aligns with global sustainability goals and holds potential for significant environmental and public health improvements.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

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