Recent Advances in Environmental Protection and Sustainable Engineering

Ravindra R. Navthar, Sandip A. Kale, Amevi Acakpovi
Editors



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Recent Advances in Environmental Protection and Sustainable Engineering

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Preface

Recent Advances in Environmental Protection and Sustainable Engineering

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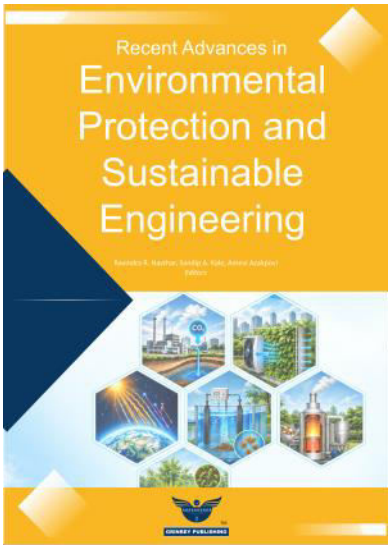
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Environmental protection and sustainable development are important challenges of the present time. Rapid industrial growth, urbanization, climate change, air pollution and wastewater generation have created serious environmental concerns. These problems require practical and scientific solutions. Engineering and technology can play an important role in reducing environmental damage and promoting the sustainable use of natural resources.

The book 'Recent Advances in Environmental Protection and Sustainable Engineering' brings together research on important environmental issues and their possible solutions. It presents studies on carbon emission reduction, air pollution control, climate change, wastewater treatment and sustainable waste management. The chapters discuss different approaches, methods and technologies that can support environmental protection.

The first chapter presents Carbon Capture, Utilization and Storage (CCUS) as a means of reducing carbon emissions from cement-based construction. Cement production is a major source of carbon dioxide emissions. The chapter reviews different carbon capture technologies, the use of captured carbon in construction materials and the economic and policy challenges involved in their implementation. It added the importance of developing low-carbon construction practices.

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The second chapter investigates the use of plants as natural air filters. Computational Fluid Dynamics (CFD) is used to study different arrangements of plant panels for removing particulate matter from air. The findings show that the zigzag arrangement provides better filtration performance than the other configurations studied. This research is useful for developing plant-based air purification systems.

The third chapter studies the relationship between solar activity, galactic cosmic rays and Earth's climate. It discusses changes in cosmic ray intensity and their possible influence on atmospheric processes and climate variability. The study also considers the limitations of the available evidence and the important role of greenhouse gases in recent climate change. It provides a useful perspective on the complex factors affecting Earth's climate.

The fourth chapter focuses on the removal of phenolic syntan from synthetic tannery wastewater using electrocoagulation. It studies the effect of operating conditions on pollutant removal and evaluates the treatment cost. The results show the potential of this method for improving wastewater treatment in the tannery industry.

The fifth chapter presents the development and experimental assessment of an induction-heated system for sanitary waste incineration. It examines the combustion behavior of different sanitary waste products and the energy required for treatment. The study explores the potential of this approach for managing sanitary waste and reducing its volume.

The sixth chapter reviews the possible use of genetically modified plants in constructed wetlands for wastewater treatment. It discusses how genetic modification may improve pollutant removal, plant tolerance and treatment performance. At the same time, it shows the need for careful biosafety assessment, environmental monitoring and suitable regulatory measures before such plants are used on a larger scale.

Hence, these chapters show that environmental protection requires a combination of scientific understanding, engineering innovation, experimental investigation and responsible decision-making. They also highlight the importance of considering cost, efficiency, safety and environmental impact while developing new technologies.

We thank all the authors for their hard work. We thank the reviewers for their time and careful comments.

We hope, this book will be useful to researchers, teachers, students, engineers and professionals working in environmental science, civil engineering, mechanical engineering and related fields. It may also encourage further research into practical solutions for environmental problems.

1

Techno-Economic Perspectives on CCUS Deployment for Reducing Process-Related CO_2 Emissions in Cement-Based Construction

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Abstract

The construction sector, and cement production in particular, is a major contributor to global CO_2 emissions, with a significant share coming from process-related sources which cannot be fully addressed by conventional measures such as efficiency improvements or substitution of materials. As mitigation strategies are reaching their limits, carbon capture, utilization and storage (CCUS) has emerged as a key path to achieve deep decarbonisation of the cement industry, which is being seen as a representative case for the wider hard-to-reach construction sector. This study presents a systematic literature review of CCUS technologies relevant for cement and concrete, based on a screening process informed by PRISMA and drawing on peer reviewed literature, technical reports and industrial case studies. The principal carbon capture pathways include pre-combustion, post-combustion, oxy-fuel combustion, and chemical looping. These pathways are evaluated alongside CO_2 utilization and storage routes such as mineral carbonation, carbonation curing, and CO_2-based construction materials. The review finds that post-combustion capture and mineral carbonation currently exhibit the highest technological readiness for near-term deployment, while emerging approaches offer long-term potential despite higher energy and cost barriers. CCUS-enabled materials also show benefits in durability, resource efficiency, and carbon permanence, though adoption remains constrained by economic, infrastructural, and regulatory challenges. Overall, the findings indicate that CCUS is essential for decarbonizing hard-to-abate construction processes, and its effective deployment will require coordinated technological innovation, supportive policy frameworks, and standardized acceptance criteria for CO_2-modified materials.

Keywords

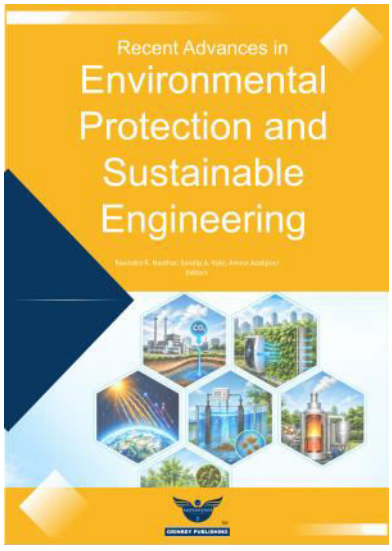
Carbonation Curing; CCUS; Cement De-carbonization; Post-combustion Capture; Sustainable Construction

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1. Introduction

The construction industry plays an important role in global economic growth, but it is also one of the largest sources of climate change because it consumes large volumes of material and energy resources [1]. Cement production is one of the most carbon-intensive industrial processes in terms of its environmental impact among construction-related activities. Latest synthesis analyses suggest that the cement sector contributes about 7-8 per cent of the greenhouse gas emissions in the world, and it is one of the biggest single industrial producers of CO_2 in the world [2]. These gases have two main sources, namely (i) process emissions coming about during the heating of limestone to release carbon dioxide chemically and (ii) energy emissions caused by the burning of fossil fuel and the use of electricity during the production of clinker [2]. Since process emissions are closely connected to the chemical changes of the raw materials, no matter how good the energy efficiency is, they cannot be completely eliminated [3]. Therefore, most commonly, cement production is listed as a hard-to-abate industry in the global plans of de-carbonization.

The issue of deep de-carbonization of industrial fields has now become burning nature in the wider framework of the Paris Agreement and the global commitment to net-zero. However, although the use of renewable energy source and electrification have greatly diminished the emissions in power and transport sector, heavy industries like cement and steel and chemicals still face structural problems associated with high-processing temperatures and process-related emissions. This is opposed to the power generation where the emissions can be diminished by switching the fuel, as cement generation intrinsically emits CO_2 in the process of forming a clinker. This inherent limitation restricts the efficiency of the traditional mitigation strategies and requires the creation of the technological solutions that will be transformative.

The cement industry is considered as a target area in global climatic mitigation agenda and de-carbonization of the industry with respect to the concentration of the sector contributing significant amounts of carbon to the atmosphere [2]. While, supplementary cementitious materials, process improvement, and partial replacement of emitting fuels can reduce carbon emissions, these strategies are not enough to achieve deep reductions in line with net-zero pathways. At that, the Carbon Capture, Utilization, and Storage (CCUS) have become one of the urgent technological ways that can resolve the residual and process-based emissions that are impossible to remove with the help of traditional mitigation methods. CCUS offers a way to achieve significant reductions to the level of the plant through the direct capture of CO_2 to the flue gases and process streams produced at the facilities and releasing them straight into the atmosphere.

This review focuses specifically on cement production as a primary sector in construction. Cement production accounts for most process-related emissions in the sector and is the clearest example of a process that is inherently hard to abate, because its main chemical reaction - calcining limestone is inherently releasing CO_2, regardless of energy source or efficiency improvements [2]. This makes cement a representative and technically instructive lens through which the wider application of CCUS in the construction sector can be examined such as: many of the capture technologies, use routes and policy mechanisms discussed (e.g. post-combustion capture, carbon capture and sequestration, carbon pricing instruments) are directly transferable to other high temperature, process-intensive building materials such as steel and glass.[4]

This review will thus (i) monitor the development and technical implementation of carbon capture systems in cement production, (ii) assess emerging CO_2 utilization opportunities in cement and concrete materials and (iii) compare the political and financial environment that will shape large-scale application in the cement industry.

Most technology evaluations show that partial implementation of CCUS can result in a reduction of emission by 60-80% especially with capture systems used on particular kiln or flue gas feeds [5]. Even more developed designs, such as post-combustion amine systems, oxy-fuel combustion, have shown technical feasibility of

capture rates over 90 percent to produce plant level reductions of emissions to around 90-95 percent under optimum operation [6]. In addition to capture and geologic storage, the construction industry has opportunities to integrate CO_2 to aid construction development in a variety of forms, such as mineral carbonation, carbonation curing, and CO_2-based construction materials, which allow long-term carbon sequestration in concrete constituents [7]. But lifecycle assessments point out that the net benefit of utilization pathways in relation to climate is reliant on how permanent the storage is, as well as the generate of carbon intensity of the energy inputs used in processing [8]. As the Indian market is becoming highly urbanized, with the cement demand expected to grow swiftly (aided by infrastructure expansion and general industrial de-carbonization), the role of CCUS in the national strategy of climate mitigation is beginning to gain more and more relevance in national climate strategies and policy discourses.

Despite increasing technological development, the incorporation of CCUS in the construction sector is still affected by economic viability, regulatory frameworks, infrastructure readiness, and market motivations. On the one hand, there are many studies of capture technologies, and as many studies that study policy or material innovation separately, but on the other hand, a synthesis of technology readiness, as well as policy systems and financial effects in regard to the construction sector are not well explored. This paper aims at presenting a systematic evaluation of the current state of CCUS as a potential de-carbonization action plan in the construction sector by considering technical, regulatory, and financial aspects.

2. Literature Review Method

2.1. Literature Search Strategy

Following the identification, screening and inclusion process in PRISMA, a systematic literature review was carried out on carbon capture, utilization and storage (CCUS) applications in the cement and concrete industries. Google Scholar was used as the primary source of literature due to its broad index of peer-reviewed articles, conference papers, and review articles in engineering and environmental science. This single database approach is recognised as a limitation in this review (see section 5). The search terms included combinations of: CCUS in cement industry, carbon capture in cement factories, mineralisation of CO_2 from concrete, carbonation of concrete, decarbonisation of cement industry and CCUS policy and economics. These searches, together with an additional snowball search of key reference lists, resulted in 86 records that were imported into the Zotero reference management software for screening. The timeframe considered for the publications is 2010-25, with an emphasis on 2016, indicating the period of acceleration of research activity and early commercialisation in this area.

2.2. Screening and Selection Requirements

After import, two duplicate records were detected and deleted, leaving 84 unique records for the name and abstract check. Records were screened against the following inclusion criteria: (i) peer reviewed journal articles or reputable conferences, (ii) published in English, or provide a direct link to the CCUS in cement or concrete or provide a basic technical background to related industrial carbon capture applications. At this stage, 10 records were excluded for non-compliance with the peer-review criterion (mainly institutional and agency reports), leaving a total of 74 records for full-text assessment. This resulted in a final set of 45 publications that were included in the summaries and reviews as shown in Fig.1. Additional sources, were found outside the primary survey, which is included in the review to support a specific empirical claim on the results of the policy incentives (section 3.5), bringing the total number of works cited in the review to 54.

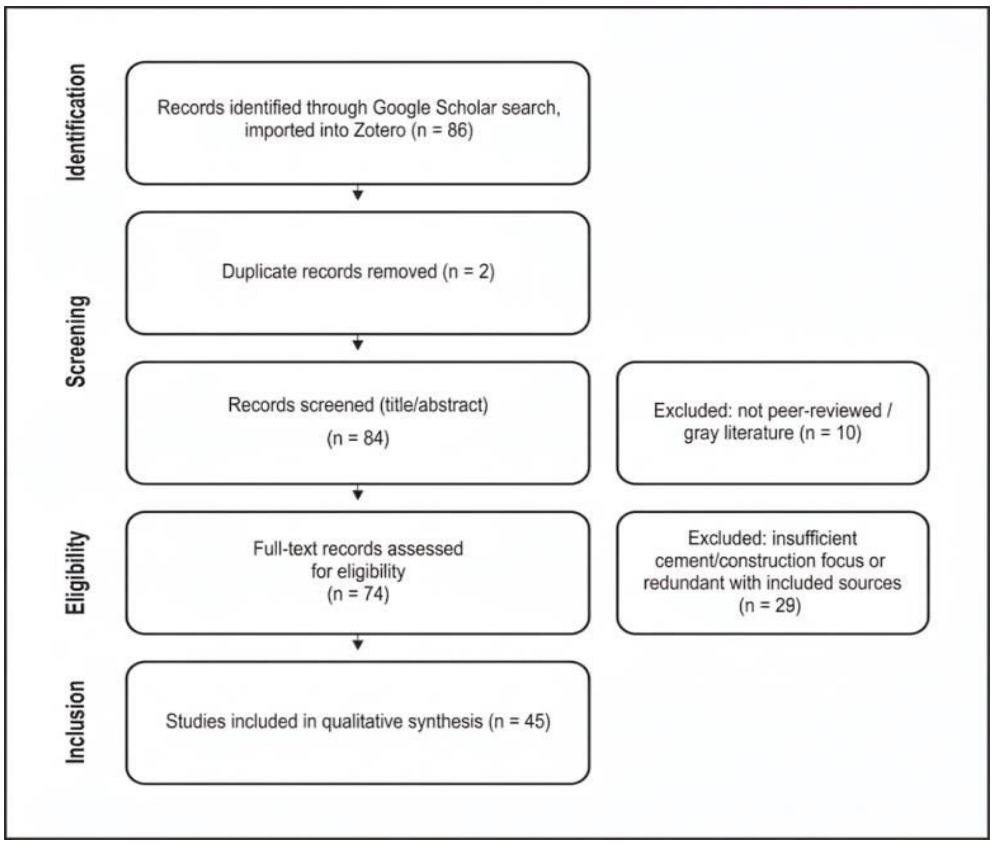


Fig. 1. PRISMA flow diagram of the literature identification, screening, and inclusion process

2.3. Data Categorization and Analytical Framework

The selected literature was then grouped into three thematic areas including (i) carbon capture methods in cement production, (ii) CO_2 use and storage routes in building materials and (iii) policy frameworks and analysis of economic viability of CCUS implementation. This grouping made it possible to compare synthesize the availability of technology, potential of emissions reduction, the mechanism of regulation, and cost implication.

3. Review Findings and Discussion

This part synthesizes the main findings from the literature review and critically reflects on technological improvements, economic factors, and policy changes related to CCUS implementation in the building industry.

3.1. Evolution and Commercialization of CCUS in Construction Industry

Based on a chronological reading of the reviewed literature, this study suggests a three-phase initial period of development of CCUs in the cement and construction industries, characterised by their development from early technological discovery to the present commercialisation efforts.

The review stresses the importance of qualitative synthesis backed by the quantitative results documented in the literature such as capture efficiency ranges, lifecycle considerations as well as cost estimates in order to have a holistic estimate on the CCUS integration in the construction industry.

Since 2010, the development of CCUS in the cement and construction industry can be simplified into three successive stages, namely the screening of technologies and the feasibility of retrofits (early-mid 2010s), the assessment of systems and the lifecycle integration (late 2010s), and the implementation net-zero-oriented approaches and early commercialization (2020s).

Phase I: Retrofit and Technology Screening (Early-Mid 2010s)

In the early 2010s, the main research focused on identifying capture technologies that could be used in cement plants. Treatment of cement was first considered as one of a number of large stationary CO_2 point source with power generation and steel production. Research focused on post-combustion solvent absorption, oxy-fuel combustion, and calcium looping and tested their technical viability and retrofit-ability to existing kiln systems. A seminal review of the literature by [6] found that post-combustion and oxy-fuel systems had the potential to capture approximately 90% of plant-level CO_2 emissions, but most applications were at pilot or demonstration scale.

Simultaneously, the initial research on carbonation curing of cast concrete indicated the technical viability of mineralizing CO_2 in concrete matrices [9].]. But at this point, the capture of CO_2 at cement kilns and its use in concrete products were virtually limited to laboratory and demonstration projects.

Phase II: Expansion System-Level and Lifecycle Assessment (Late 2010s)

After the Paris accord in 2015, the focus on research shifted to the assessment of CCUS in the context of decarbonization pathways. Instead of concentrating on capture efficacy, research started to utilize the life-cycle evaluation (LCA) methodologies to evaluate net climate effects. As it has been reviewed, the environmental performance of carbon capture and utilization (CCU) pathways are considerably dependent on carbon intensity of electricity and methodological boundaries that are regularly followed [3].

At the same time, the literature began to view cement as an industry that is hard to abate with CCUS becoming a necessity rather than an option in the case of deep emissions cuts [10], [11]. Integration studies involved combined capture-utilization chains, such as synthetic fuel production and methanol pathways, and highlighted high energy demand and cost sensitivity [3]. It was a conceptual transition to single capture technologies to the analysis of integrated CCUS systems.

Phase III: Net-Zero Framing and Early Commercial Deployment (2020s)

By the 2020s, CCUS in cement has emerged as one of the core points of net-zero industry policies [2]. Studies were broadened in their technical feasibility to techno-economic modelling, regulations, financing systems, and implementation routes. CO_2 mineralization, carbonation curing and CO_2-based construction materials are now being viewed as promising early-commercial technologies in reviews in the civil engineering community [7], [8], [12].

Although capture at integrated cement plants is mostly at pilot and early-commercial stage, it has since the mid-2010s become a more routine part of commercial practice in precast and specialty concrete products. CCUS facilities in all industries worldwide have increased dramatically, but cement accounts for only a small percentage of overall capacity [13]. Carbon pricing and tax incentives (e.g., 45Q in the United States) as policy instruments and green procurement standards have played an essential part in increasing the pace of deployment after 2015 [2], [14].

The general trend of CCUS in cement is that it is now moving towards feasibility of concept to show system-level integration and early commercialization. Nevertheless, full-chain capture, transport, and storage in the production of clinker are only becoming prevalent as opposed to established, and the cost, infrastructure, and regulatory coordination of this technology are still determining its scalability [15].

3.2. Carbon Capture Technology in Construction Industry

3.2.1 Cement Production and Mechanism and CO_2 Sources.

The average tonne of cement produces around 600-900 kg of CO_2, equivalent to approximately 7-8 percent of anthropogenic CO_2 emissions worldwide [6], [3]. There are two main sources of emissions; the reported ratios vary slightly in the literature depending on the chemical composition of the clinker, the fuel mix and

the kiln technology. The calcification of limestone ($CaCO_3$ + CO_2) is an inevitable consequence of the chemical process itself. It accounts for 60-70 percent of emissions, although estimates vary between 50-70 per cent [2], [8]. The remainder, about 30 to 40 per cent, is due to the burning of fossil fuels to maintain the furnace temperature at more than 1450°C [3], [16]. As calcination emissions are chemically inherent in cement production, no amount of energy savings or substitution can fully eliminate them, which makes carbon capture a critical mitigation measure [6].

Carbon capture systems in cement plants are mainly applied to the kiln and precalciner exhaust gases, which contain both combustion and process CO_2. The CO_2 concentration of the cement combustion flue gas varies considerably (14-33%), showing both the specific point of extraction of the process. The off-gas of the pre-calcification process is usually more CO_2-rich due to concentrated emissions. Whereas, the main kiln burner exhaust is diluted by combustion of air nitrogen and has wider variability across plants depending on fuel mix, kiln configuration, and use of oxygen enrichment [10]. This range still indicates that the industry is technically well placed to integrate capture with other factory emissions [10].

3.2.2 Pathways of Capture Technology in Cement.

There is post-combustion, oxy-fuel, calcium looping, and direct separation technologies that can be used used in capturing carbon in cement. Post-combustion capture resembles the principle behind the scrubbing process.

a. Post-Combustion Capture (Amine Scrubbing)

The principle of post-combustion capture is similar to the scrubbing process. The most mature and demonstrated capture option is post-combustion solvent absorption. This is done by passing the flue gas through an absorber column filled with chemical solvents (e.g., monoethanolamine), through which CO_2 is selectively absorbed. The solvent is then regenerated by thermal stripping, which emits concentrated CO_2 for compression and storage [6], [10]. It has been reported that the capture efficiencies in treated streams are in the 85-95% range, but energy penalties related to solvent regeneration are large [16]. The main benefit of this method is that it is retrofit-compatible with the existing kilns.

b. Oxy-Fuel Combustion

Oxy-fuel systems substitute air with almost pure oxygen in the combustion process and result in a clean gas that consists mainly of carbon dioxide and water vapour. A stream of high-quality CO2 is obtained after condensing the water, making the separation complex reduced [3], [6].

Though it can capture at high rates, oxy-fuel needs large kiln redesign and expensive air separation units, which is better applied in new installations or when changing the whole plant [17].

c. Calcium Looping (CaL)

Calcium looping involves using a circulating cycle of $CaO/CaCO_3$ to absorb CO_2 using flue gases in a carbonator reactor and then release concentrated CO_2 during the calcination process. Because of the chemical compatibility of CaO and cement raw materials, this technology has integration benefits in clinker production [16]. The reported capture efficiencies are greater than 90 percent, and CO_2 purity is high (99 percent), making CaL one of the most promising cement-specific capture methods [6], [16].

d. Direct Separation Concepts

New designs like indirect heating or calciner redesign (e.g., direct separation reactors) are being developed to produce almost pure process CO_2 during limestone calcination and then separate it prior to combustion emissions before it is mixed with them. Although the systems are conceptually appealing in reducing energy penalties, they are current at the laboratory level to pilot [6].

3.2.3 Commercial Deployment and Technology Readiness Level (TRL)

The TRL classifications discussed below are based primarily on one industrial CCUS assessment [13]; while they are broadly in line with the TRL ranges reported elsewhere in the literature on capture technologies, precise attribution of TRL may differ from assessment to assessment depending on the criteria and the industry context used and should be treated as indicative rather than final.

Technology readiness levels (TRLs) offer a systematic way of assessing the maturity of carbon capture technologies between laboratory (TRL 1-3) and commercial (TRL 8-9) operation [18]. According to industrial CCUS evaluations [19], there are capture technologies that can be utilized in cement and they could be classified as follows.

a. Post-Combustion Capture (TRL 8-9)

Solvent-based post-combustion systems are the most mature carbon capture technology that is available at the moment. Having TRLs of 8-9, such systems are commercially implemented in a number of industries. They have a major advantage in that they can be retrofitted to the existing cement kilns. Nevertheless, drawbacks such as high energy penalty for solvent regeneration, solvent degradation, and operational issues driven by corrosion are also significant [19], [20].

Though proven commercially in other industries, large-scale implementation in cement is limited but in early stages of commercial implementation.

b. Pre-Combustion Capture (TRL 7-8)

In pre-combustion systems, CO_2 is captured before combustion in syngas streams (H2 + CO_2) in pre-combustion devices that recover CO_2 before the combustion process, which in most cases is an integrated gasification combined cycle (IGCC) system. These technologies have been proven to be 7-8 TRLs; however, they are typically not applicable to new plants and can only be integrated into complex plants, which are expensive [6], [19]. Pre-combustion routes are not as prevalent in cement because they do not fit in typical kiln designs.

c. Oxy-Fuel Combustion (TRL 6-7)

Oxy-fuel combustion is located on TRL 6-7 and is associated with pilot and small-scale industrial demonstrations. The flue gas produced is rich in CO_2 when fuel is burned in almost pure oxygen, making it easy to separate. A large air-separation unit, the cost of oxygen production, and material restrictions, however, continue to be serious obstacles to full commercial use [19]. Oxy-fuel in cement is promising but requires major alterations to the kiln.

d. Chemical Looping Combustion (TRL 3-5)

Chemical looping, which uses metal oxides as oxygen carriers to separate CO_2 inherently during combustion, is at TRL 3-5. Development is currently mostly limited to laboratory and initial pilot stages. Some of the challenges include the lifetime of oxygen carriers, the complexity of reactor scale-ups, and the lack of large-scale demonstrations [20].

Although post-combustion systems have been commercially demonstrated in some industrial sectors, their use in cement is at early commercial or advanced demonstration phases, oxy-fuel and looping remain in the pilot validation phase. Table 1 outlines the TRL levels, deployment status, and major limitations of major carbon capture technologies relevant to cement production.

The reported capture efficiency of CaL (90%) and CO_2 purity (99%) reflect performance demonstrated in laboratory and pilot studies under supervised conditions rather than commercial-scale operational capability.

TRL is explained because of factors other than chemical performance, including sorbent (CaO) degradation during repeated carbonation-calcification cycles, problems with reactor expansion, and issues in integrating with existing furnace systems. This explains why CaL remains below TRL (3-5) despite the positive performance figures. The difference between demonstrated chemical performance and full system readiness is a common pattern across emerging capture technologies and is not unique to CaL.

Table 1. TRL for different Carbon Capture processes

Capture Process	Technology Description	TRL	Status	Key Limitations
Post-combustion Capture	CO_2 separation from flue gas using solvents (e.g., amines)	8–9	Commercially deployed	High energy penalty, solvent degradation, corrosion
Pre-combustion Capture	CO_2 capture from syngas (H_2 + CO_2) before combustion in IGCC systems	7–8	Demonstrated, limited to new installations	High capital cost, complex plant design
Oxy-fuel Combustion	Combustion in pure O_2 yields CO_2-rich flue gas	6–7	Pilot and small-scale industrial plants	High oxygen production cost, material constraints
Chemical Looping Combustion	Indirect combustion using metal oxides for inherent CO_2 separation	3–5	Lab-scale and early pilot testing	Oxygen carrier durability, reactor scale-up, limited demonstration

Source: TRL classifications from [13]; ranges are generally in line with other cited literature on capture technologies but should be considered as indicative and not final.

3.3. CO_2 Utilization in Cement and Concrete

The application of carbon dioxide in the cement and concrete value chain is mainly founded on the mineral carbonation, during which CO_2 combines with calcium- or magnesium-rich phases to produce stable carbonate minerals. As opposed to short-lasting chemical routes of utilization, mineralization pathways provide long-term storage of construction materials and thus high climate mitigation potential in the long term [12], [22].

3.3.1. CO_2 Curing of Precast Concrete

Accelerated carbonation curing applies fresh or young concrete to a condition of higher CO_2 levels in controlled pressure and humidity. The CO_2 dissolves in the pore solution and reacts with calcium hydroxide, unhydrated clinker phases, and C-S-H gel to create stable CaCO3. This reaction increases the density of the microstructure and promotes early strength development [4], [14].

The uptake of material at the material scale differs greatly with mix design and curing regime. According to laboratory research, uptake of up to 17% of cement mass has been observed in a high-purity CO_2 environment, and in commercial precast, the uptake is more in the 0.01-0.05 t CO_2/ton of concrete range [12], [23]. On a bigger scale, it has projections that, based on high adoption rates, precast carbonation curing has the potential to remove CO_2 at the gigaton level per year [23].

The two figures are not directly comparable: the laboratory value represents the CO_2 content of the proportion of the reactive cement and binder in idealised high purity conditions, while the commercial value represents

the total CO_2 content of the finished concrete unit, which includes the aggregate, water and other non-reactive components diluting the percentage.

Notably, the thermodynamic stability of the carbonates formed is on building time scales, meaning that they store well in the long term [24].

3.3.2. CO_2 Injection during Mixing (Ready-Mix Systems)

Small doses of liquid CO_2 (typically1.5% of cement mass, roughly 5 kg/m3) are added to the mix by injection. About 50-80 percent of injected CO_2 mineralizes into nano-$CaCO_3$, resulting in permanent storage of about 2.5-4 kg CO_2/m^3 of concrete[8], [25].

The direct mineralized amount is small but the strength benefit provided by the creation of nano-$CaCO_3$ facilitates cement decreases of about 5 percent, frequently dominating the overall emission sparing [22], [26]. Thus, the climate gain of injection systems is motivated more by that of the reduction of clinker than pure CO_2 uptake.

3.3.3 Mineralization of carbonated Aggregates and Industrial Waste

A further significant route of utilization is ex-situ mineralization of alkaline industrial residues including steel slag, fly ash, red mud and cement kiln dust. The mentioned Ca/Mg-based solids are reacted with concentrated CO_2 in special reactors to produce carbonate-bound aggregates or binder precursors [7], [22].

The uptake is reported to range from around 0.09 to 0.44 t CO_2 per ton of aggregate, depending on feedstock and process conditions [12], [23]. In addition to storing carbon, these pathways increase circularity by diverting industrial wastes from landfills and reducing the need to use virgin aggregates.

The recycled concrete aggregates (RCA), which are carbonated, also demonstrate better resistance and a lower water uptake following the accelerated carbonation exposure [8], [12]. On a feasible scale, the annual production of iron and steel slags worldwide is estimated to be more than 400 million tonnes, and the mineralisation of these slags alone yields a potential for global CO_2 savings of ~0.1-0.15 Gt per year, equivalent to a fraction of global anthropogenic emissions. This suggests that mineralisation routes from industrial waste, although valuable for circularity and localised emissions reduction, are unlikely to compensate for the gigatonnes of emissions of the cement sector alone; their main contribution is to complement, rather than replace, capture-based decarbonisation of the cement kiln itself.

3.3.4 CCU to Cement-Integrated Fuels and Chemicals

The CO_2 captured in cement plants can also be used with hydrogen to form methanol, urea, or methane as well as other synthetic fuels in integrated CCU [3], [16]. Nevertheless, the analysis of life-cycle assessment invariably shows that such routes need very low-carbon electricity to yield net reductions in emissions and typically have reduced long-term mitigation efficiency than permanent mineralization pathways [3].

3.3.5 Life-Cycle Assessment Perspective

Life-cycle assessment shows that the use of CO_2 in concrete is not necessarily associated with net climate benefit. A significant part of the captured CO_2 can be compensated by upstream capture energy, CO_2 purification, compression, and transportation [22], [23].

The net benefits are the strongest when:

- Low-carbon energy sources CO_2.
- The distances of transport are insignificant.
- Cement or steam-curing savings are obtained significantly.
- There is high mineralization efficiency.

In many cases, precast carbonation curing systems with clinker reduction can show more apparent life-cycle benefits compared to small-dose injection systems [12], [26].

3.4. Geological Storage of CO_2 from Cement Plants

Geological storage represents the most mature and large-scale option for managing CO_2 captured from cement plants. Unlike utilization pathways, which are constrained by material demand, subsurface storage offers multi-gigaton capacity and is considered essential for deep decarbonization of hard-to-abate sectors [10], [26].

3.4.1 Storage Formations

a. Deep Saline Aquifers

Deep saline formations located at depths greater than ~800–1000 m allow CO_2 to exist in a high-pressure state, boosting storage density. These geological formations are widely distributed globally and are considered the largest potential storage resource [10], [13].

Advantages include:

- Very large potential capacity
- Geographic flexibility
- No dependence on hydrocarbon production
- Strong long-term structural and residual trapping mechanisms
- Saline aquifers are therefore prioritized in long-term CCS deployment strategies.

b. Depleted Oil and Gas Reservoirs

Depleted hydrocarbon fields offer proven caprock integrity, existing infrastructure, and well-characterized geology. In many cases, CO_2 injection can be coupled with enhanced oil or gas recovery (EOR/EGR), generating economic value during early deployment phases [26], [27]. These storage sites are particularly attractive when cement plants are located near mature hydrocarbon basins.

c. Coal Seams and Mafic Formations

Unmineable coal seams enable CO_2 adsorption and methane displacement (ECBM), though total storage potential is smaller and reservoir evaluation is more complex [4].

Mafic and ultramafic formations (e.g., basalts) allow in-situ mineralization, converting injected CO_2 into stable carbonate minerals. While this pathway offers high permanence, it remains more site-specific compared with saline aquifers [28].

3.4.2 Global and Indian Storage Capacity

Geological storage capacity is estimated to be on the order of thousands of gigatons globally. One synthesis reports theoretical global capacity approaching ~11,000 Gt CO_2 across sedimentary formations [13].

The United States alone is estimated to possess >2,400 Gt CO_2 storage capacity across saline aquifers, hydrocarbon reservoirs, and coal seams [13].

As with most assessments of geological storage, the figures for both the world and the US are based on a single synthesis source [13] and reflect theoretical storage capacity rather than the available capacity in practice; actual injection volumes are usually only a fraction of the theoretical volume once geological, regulatory and technical constraints are applied.

For India, latest evaluations estimate geological storage capacities ranging from about 500 to 1,000 Gt CO 2, including sedimentary and basaltic formations [20]. This estimate reflects an assessment at national level; as

estimates of geological storage capacity are highly sensitive to the assessment methodology used (e.g. theoretical versus actual capacity), this figure should be considered as an indicative figure pending more in-depth mapping of the source and sink, rather than an exact or definitive national inventory. This suggests that the availability of storage is unlikely to be a constraint to the long-term de-carbonisation of the cement industry in India, although an in-depth mapping of source and sinks remains to be done.

3.4.3 Operational Deployment and Case Studies

Large-scale geological storage has been operational for over two decades.

Notable examples include:

- Sleipner (Norway), injecting ~0.8–1 Mt CO_2 per year into a saline aquifer since 1996
- Snøhvit (Norway), offshore saline storage associated with gas production
- In Salah (Algeria), deep saline injection project
- Weyburn–Midale (Canada), CO_2-EOR combined with long-term storage

In the United States, CO_2-EOR operations in the Permian Basin have injected millions of tonnes annually, with a significant fraction remaining geologically stored [14].

Recent offshore developments in China, including the Enping 15-1 project, indicate the emergence of hub-scale storage systems [29].

These projects demonstrate that geological storage has reached commercial-scale deployment, particularly in saline aquifers and hydrocarbon reservoirs.

3.4.4 Risks and Monitoring

Long-term risks primarily include:

- Leakage through faults or wellbores
- Groundwater acidification
- Induced seismicity
- Pressure-induced geomechanical effects

However, well characterised sites are expected to retain >99 per cent of the injected CO_2 over a centennial time scale (i.e. ~100 to 1000 years after injection, as typically modeled in geological storage risk assessments) due to structural, residual, solubular and mineral trapping mechanisms, with the latter becoming dominant over time [13].

Effective implementation requires comprehensive Measurement, Monitoring, and Verification (MMV), including:

- Continuous pressure and injection monitoring
- Time-lapse seismic imaging
- Geochemical and tracer studies
- Surface and soil-gas surveys

3.4.5 Geological CO_2 storage Regulatory Framework

Although the technical feasibility of geological storage technologies has been demonstrated, large-scale implementation is mainly limited by regulatory uncertainty rather than technical restrictions. The literature emphasizes that the allocation of long-term liability, the right to own pore space, the right to monitor and verify, and the obligation to maintain stewardship after closure are among the key areas of legal concern [30], [31], [32]. Truncated permit systems and ambiguous environmental compliance criteria in most jurisdictions

extend the project approval process and raise investment risk. Moreover, the lack of uniform international regulations regarding the transportation of cross-border CO_2 and offshore storage is an added legal complication. Such regulatory uncertainty significantly affects investor confidence and the bankability of the project, especially for first-of-a-kind cement CCUS installations.

3.5. Carbon Pricing and Economic Instruments

The key factor in influencing the implementation of CCUS in the cement industry is carbon pricing. According to empirical and modeling research, moderate or fluctuating carbon prices are generally not high enough to motivate significant capital investment in capture and storage infrastructure [33], [34]. Evidence from emissions trading schemes indicates that carbon prices are stable and sufficiently high when complemented by complementary schemes, including tax credits, investment subsidies, contracts for differentiated services, and carbon border adjustment schemes. Examples of policy instruments such as the 45Q tax credit in the US and the Innovation Fund in the EU have demonstrated the importance of some financial incentives to drive industrial de-carbonisation at an early stage. In the US, the 45Q loan was linked to more than 150 proposed CCS projects covering electricity generation, cement, chemicals, gas processing, and the concrete sector; sector-specific analyses estimated significant related employment and economic impacts linked to projects that would not have been undertaken without the loan [35]. Cement producers will not invest heavily in the CCUS until price certainty is guaranteed in the long term [36].

3.6. Governance of infrastructure, Transport Networks and Storage

Beyond capture economics, unit costs are reduced through the development of shared CO_2 transport and storage facilities, which demand industrial clustering. Hub-and-cluster models, in which several emitters use pipelines and storage reservoirs, improve economies of scale and decrease risks associated with single projects. Infrastructure planning, however, requires policy support, collaboration between the government and businesses, and government intervention to ensure regulatory transparency on third-party access rights, tariffs, and inter-sector integration to create effective CO_2 transport networks. Poor characterization of storage site information and restricted geological surveys also delay infrastructure planning, especially in developing economies.

3.7. Policy Environment and Business Obstacles in India

CCUS implementation in India is also at an early stage, and its adoption is mostly facilitated by strategic roadmaps and pilot projects rather than a full regulatory statute. Policy deliberations at a national level, such as reports by NITI Aayog and sectoral decarbonization pathways, note that CCUS is an infrastructure-level technology that can be fundamental in reaching long-term net-zero goals within sectors like cement, which are hard-to-abate. Commercialization is, however, limited by barriers such as high capital costs, a lack of specific financial incentives, inadequate transport infrastructure, and a lack of well-established frameworks of long-term liability [4], [37], [38]. Besides, the changing carbon market structure in India remains in an initial phase, and the lack of a well-established mechanism to price carbon decreases economic incentives towards the use of CCUS. Although pilot mineralization and utilization projects are coming into place, full-scale geological storage governance structures are still not institutionalized. These structural and financial gaps will require attention to move to commercial application in the cement sector in India.

4. Future Direction

The shift of the CCUS in the cement industry out of pilot demonstrations to a system-wide implementation will need co-ordinated technological, infrastructure, governance, and digital integration progressions. Recent literature shows that conceptual feasibility is no longer the major bottleneck; instead, cement-specific scale-up, system integration, and market structuring have become the critical bottlenecks.

4.1 Scale-Up of technology and Cement-specific integration

One of the most significant research gaps is the development of capture systems (TRL 5-6) to commercial systems (TRL 7-9) operating in cement-specific routes including oxy-fuel combustion systems, calcium looping systems, and indirect calcination systems (e.g., LEILAC) [3], [6]. Mass retrofit engineering, kiln-capture heat integration, space considerations and sequential renovation of plants are areas that are not explored enough. Further improvement with the help of waste heat recovery and low carbon integration is needed to further reduce the 10-20 percent energy costs associated with solvent recovery in post combustion amine-based capture systems [39].

In addition to capture units, system level design is not well researched. Small studies assess committed transport networks to deliver cement clusters, source-sink compatibility, policy uncertainty, and connections to local storage centers [7], [10]. Region-specific evaluations of CCS versus CCU versus combined routes under realistic grid carbon intensities are also limited [25], [40].

4.2 Usage Patterns and Market Creation

Carbonation curing, CO_2 mineralization, and CO_2-based binders are additional avenues of utilization that need to be further legitimized over the long term; nonetheless, the durability, kinetics, and performance of these materials on waste streams and mix-designs need to be validated [12]. There should be harmonized approaches to the lifecycle accounting to prevent the cases of the duplication of counts and healthy claims on carbon removal [40]. As a way of scaling up utilization markets, market-pull mechanisms such as green public procurement, product standard of low-carbon cementitious materials are viewed as crucial [24].

4.3 Policy Innovation and Business Model Development

Further studies also need to deal with cement-specific business models that connect capture facilities with transport and storage networks. Risk-sharing schemes, contracts-for-differences, price stability in relation to carbon prices, and liability systems continue to be key factors behind the decision to invest [33], [41], [42]. Models of a carbon hub cluster and a staged infrastructure implementation are broadly suggested as the ways to lower the price per tonne captured [43], [44].

Emerging literature also focuses more on sociotechnical aspects of the topic, such as social acceptance, environmental justice, and transparency in governance, which are less represented in studies on the cement sector [41], [45].

4.4 Optimization of Systems and Digitalization.

A major but unexploited opportunity by cement CCUS is presented by digital technologies. Hybrid models that use AI and model predictive control have also proven to increase the energy efficiency of cement plants and have the potential to optimize kiln-capture [46], [47]. Machine learning applications are useful for predicting solvent performance, real-time process optimization, and detecting faults in capture systems [29], [48].

In the case of geological storage, digital twins that combine both reservoir dynamics simulation and real-time observation of data enable dynamic injection control and early leak identification [49]. AI-enhanced lifecycle assessment systems also enable adaptive assessment of the environment to changing operating conditions [50], [51]. Nevertheless, all-inclusive digital CCUS systems that suit cement plants are mostly abstract.

4.5 Cement Industry in India Strategy.

Synergising projections across national policy plans [28], [29] the development would be gradual: pilot and cluster development in the 2020s, infrastructure development in the post-2030s and, depending on policy and

financial incentives, more extensive integration into industrial de-carbonisation trajectories from 2035 to 2050.

The implementation of CCUS in India will proceed slowly. At present, work remains limited to demonstrations and use-oriented projects [37], [38]. Short-term obstacles include capture costs, the lack of transport infrastructure, and the changing regulatory framework [52], [53]. However, modeling research indicates that CCUS will also be essential to reduce the cement industry's process emissions in India by mid-century, especially under net-zero 2070 pledges [54].

5. Conclusion

The cement industry is also one of the most problematic industries to decarbonize because it has a dual emission profile, consisting of energy-related and unavoidable process emissions from limestone calcination. Although incremental changes in energy efficiency, clinker replacement, and the use of alternative fuels can reduce carbon emissions, they cannot meet deep decarbonization goals on their own. Carbon Capture, Utilization, and Storage (CCUS) is thus not a peripheral solution, but a structural requirement towards long-term net-zero solutions in the cement industry.

As evidenced by the review, capture technologies including post-combustion absorption, oxy-fuel combustion, calcium looping, and indirect calcination have developed considerably in the technology readiness spectrum, with several pilot and demonstration programs preparing to scale up to early commercialisation. Nevertheless, these technologies are still limited by large-scale integration issues, energy penalties, infrastructure reliance, and cost uncertainties, which inhibit rapid adoption. Storage routes are technically well-developed, yet they need coordinated transport network development and clear regulations. The Use method, in particular CO_2 mineralisation, shows good prospects for circular economy synergies, although the net climate benefit varies greatly between them. In some cases, notably for CO_2 injection into a ready mix; significant proportion of the reported emission benefit is due to the associated reduction of the clinker in the composition rather than the CO_2 itself, which points to the need for a standardised lifecycle accounting to separate these two contributions and allow for long-term verification of the carbon sequestration claims.

CCUS feasibility is increasingly influenced by policy and governance structures. The major facilitators include stable carbon pricing systems, financial de-risking instruments, and infrastructure models, as well as clusters and harmonized monitoring-reporting-verification (MRV) systems. In India,, with cement demand expected to rise further as a result of infrastructure development, CCUS is expected to play a decisive role in residual process emissions under the national net-zero commitment in 2070. Nevertheless, preliminary pilots, positive regulatory tools, and industry clustering plans should be accelerated to close the demonstration and deployment periods.

Future research directions should focus on cement-specific system integration, cost-reduction avenues through modularization and scale learning, digital optimization schemes, and regionally specific techno-economic analyses. There will be a need for greater interdisciplinary coordination between materials science, process engineering, infrastructure planning, digital analytics, and policy design. Finally, technology maturity will be key not only to the viability of CCUS in cement alone, but also to the concerted actions taken at technical, economic, and institutional levels.

CCUS is, in this regard, a disruptive but multidimensional course of action: one that, when wisely implemented, could bring together the essential contribution of the sector to the growth of the global economy with the goal of climate stabilization.

Abbreviation

CaL	:	Calcium Looping
CCS	:	Carbon Capture and Storage
CCU	:	Carbon Capture and Utilization
CCUS	:	Carbon Capture, Utilization, and Storage
ECBM	:	Enhanced Coalbed Methane recovery
EGR	:	Enhanced Gas Recovery
EOR	:	Enhanced Oil Recovery
IGCC	:	Integrated Gasification Combined Cycle
LCA	:	Life-Cycle Assessment
LEILAC	:	Low Emissions Intensity Lime and Cement (project)
MMV	:	Measurement, Monitoring, and Verification
MRV	:	Monitoring, Reporting, and Verification
PRISMA	:	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TRL	:	Technology Readiness Level

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2

Investigations on Effect of Different Strategies for Air Pollution Treatment with Plants as Air Filter: A CFD Analysis

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Abstract

The objective of the present research work is to investigate the effect of implementing various types of plant panels on air quality characteristics, such as the removal of particulate matter (PM10) particles, using CFD simulation. This study finds the inclusion of three different types of plant filter panels, such as blocking, parallel, and zigzag forms. CFD simulation was performed using ANSYS Fluent, considering steady state conditions within a range of 0.5-2.0 m/s for air inlet velocities. It was found that the zigzag arrangement of panels has resulted in highly turbulent and mixed flow, as compared to the parallel configuration, which resulted in smooth flow, and the blocking configuration has produced low-velocity zones of recirculation. Besides this, it was also revealed through CFD simulation that PM10 mass flow was lowest for zigzag, minimum for blocking panels, and intermediate mass flow of PM10 particles for parallel. In summary, it was gathered that zigzag panels yielded superior filtration, uniform air flow as compared to the other two configurations, especially in the velocity range of 1-1.5 m/s.

Keywords

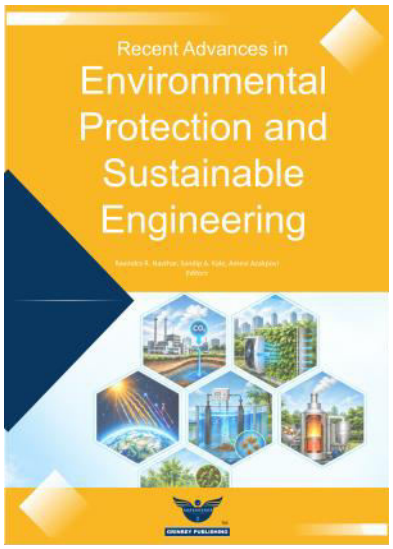
Computational Fluid Dynamics; Plant-Based Air Filtration; Particulate Matter (PM_{10}) Removal; Sustainable Air Purification; blocking; zigzag; parallel.

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1. Introduction

Environmental degradation is increasing rapidly, especially through air pollution. Air pollution occurs due to both natural sources and human activities, degrading the quality of air both within and outside buildings [1]. In this context, it was observed that major sources of air pollution include exhaust from vehicles and industries, the use of fossil fuels, and heavy construction and mining activities [2]. Again, it was gathered that major air pollutants were seen as particulate matter, carbon monoxide, carbon dioxide, and nitrogen oxides. Ozone and Volatile Organic Compounds, which degrade the quality of air [3,4,5]. It was observed that within buildings, burning of wood and coal, usage of construction materials, and dreadful human activities degrade the environment in terms of air pollution [6,7,8]. In the scenario of indoor air pollution, both Li and Hutzel [6] and Yu et al. [7] gathered that improper and a lack of ventilation is another major cause of indoor air pollution. On the other hand, it was gathered by Wang et al. [8] that the implantation of air filtration systems reduced the level of indoor air pollution.

It was gathered that the plantation of plants and trees within the ecosystem and promotion of green infrastructure for the removal of elements causing air pollution [9,10,11,12]. In this context of removal of air pollutants, Tran et al. [9] worked on the effectiveness of planting trees in the urban environment, which helps in reducing pollutants from the air. On the contrary, Cai et al. [12] utilized the technique of CFD analysis for the investigation of air purification based on vegetation. In addition to this, it was also found that plant-based biofilters can capture the particulate matter, which is dependent upon the velocity of air [13,14]. In another investigation, it was also found that optimizing the flow of air within the plant chambers can be achieved by proper placement of a fan, which in turn resulted in uniformity of air and photosynthesis [15]. Again, in this scenario, it was gathered that the Azolla-based biofilter system emerged as a sustainable solution for the removal of pollutants residing within buildings for low-carbon generation [16]. It was gathered that through all these investigations proved that by optimizing the flow of air, density of vegetation, and through proper selection of correct species of plant filters, the effectiveness of filtration and the proper reduction of pollutants.

It was also gathered that for the reduction of air pollution, vegetation in the urban environment has played a major role. Researchers in the past observed that particulate matter levels can be reduced through the implementation of large green spaces such as Tehran's Pardisan Park via dispersion [11]. Besides, it was also found that the shape of trees helps in the spreading of pollutants [10]. Some other researchers found that arrangements of vegetation in clustered manner with optimized green coverage helps in reduction of both carbon monoxide and as well as that of particulate matter [9,12]. In addition to the above investigations, additional efforts by researchers found that this system of plant filter systems has proven to be an economical and sustainable approach for the reduction of PM levels [17,18].

Besides CFD modelling and simulation approaches, artificial intelligence driven has revolutionized the prediction of air quality purification and pollutants removal rate. In this context, it was found by researchers that the employment of AI-based prediction models (CFD-CNN-GRU frameworks) proved to be highly effective in capturing the amount of PM 2.5 particles and can also help in optimizing the performance of plant-based filtration systems. Besides the integration of CFD and AI-based approaches, digital twin found to be highly effective in continuous and real monitoring of plant-based filtration systems [2,3,5,19]. Besides this, it was gathered that solar-powered cleaning systems help in reducing $PM_{2.5}$ and CO_2. It was also found that within the scenario of industrial and waste treatment for pollutants dispersion for industrial scenarios, it can be predicted effortlessly via CFD simulation [5].

It was gathered from the above literature review that there are three major factors, namely vegetation-based filtration, CFD-driven optimization, and data-driven modelling, which majorly control the quality of air in a sustainable form. Therefore, in the present study, three major configurations of plant filters, namely blocking, zigzag, and parallel, were derived to assess the effectiveness of air quality and pollutant removal using CFD simulation in ANSYS Fluent 21 [14]. The output of the CFD simulation was expressed in the form of four different field variables, such as air velocities, PM 10 particle velocity, temperature, and particle trajectories. This study aims to find the most efficient configuration for maximizing pollutant removal and promoting the development of sustainable, plant-based air purification systems for both indoor and urban environments.

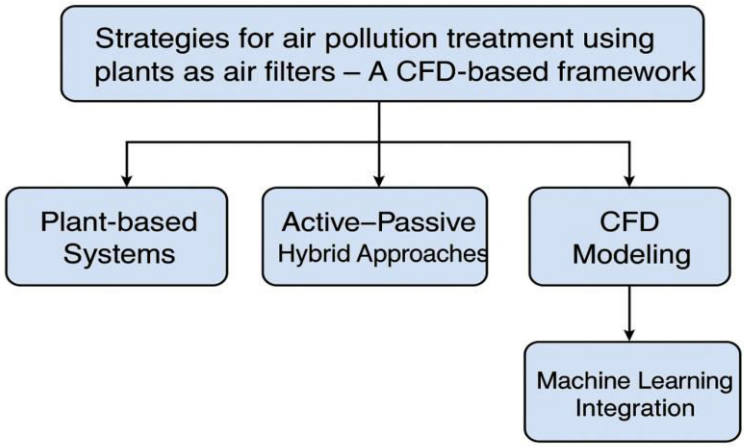


Fig. 1. Various strategies for air pollution treatment using plants as air filters based on CFD based framework

2. Materials and methods

The following section gives the materials and methods for the present work.

2.1 Geometrical modelling and Preprocessing

In the present work for the purpose of CFD analysis, the first step is to create a geometric model of the plant-based filtration which is rectangular form having dimensions of 100 × 80 × 30 cm along with two openings of 10 × 10 cm size at inlet and outlet of the rectangular chamber. Different CAD models were prepared for blocking, parallel and zigzag patterns so as to assess the effect of inlet air velocity on the average air velocity at inside and outlet and as well as on the PM_{10} particles removal due to such type of arrangements. Figures 2 to 4 show the CAD representations for each configuration. Figure 5 presents the overall methodology used for this CFD study.

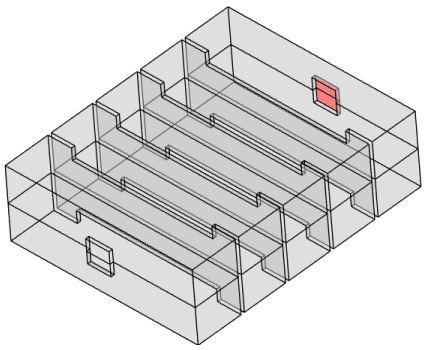


Fig. 2. Air-filtration-Plants-Blocking panels

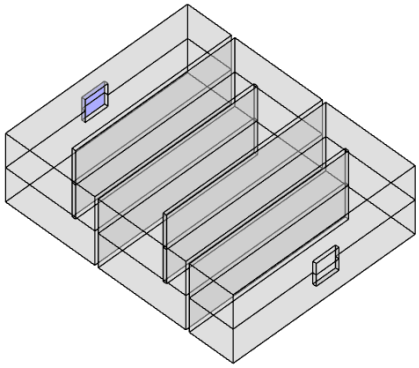


Fig. 3. Air-filtration-Plants-zigzag-panels

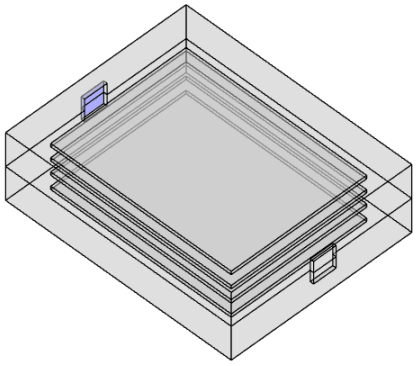


Fig. 4. Air-filtration-Plants-parallel panels

2.2. Mesh Generation

After preparation of CAD models, the next step within CFD analysis is to generate meshing of the prepared model. In the present analysis, model is mesh using unstructured tetrahedral grid of element grid size of 2.5 mm was considered, which was capable of replicating the complex behaviour of plant panels. Skewness and orthogonal quality were checked for ensuring the quality of mesh for achieving convergence condition as well as mesh independence tests was also performed to before fixing the mesh size. Meshed models of rectangular chamber are shown in Figures 6, 7, and 8 for blocking, zigzag, and parallel panel configurations, respectively.

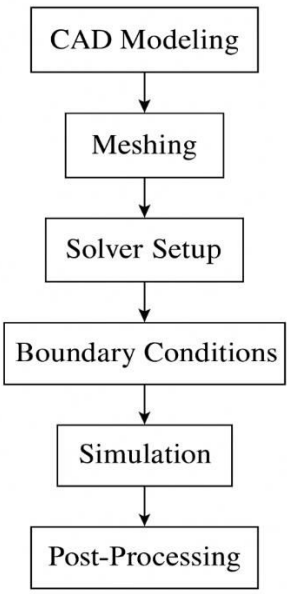


Fig. 5. Methodology adopted during the CFD analysis of air filtration with plants as filter

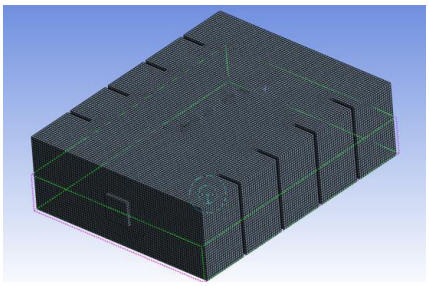


Fig. 6. Mesh model of air-filtration-plants-blocking panels

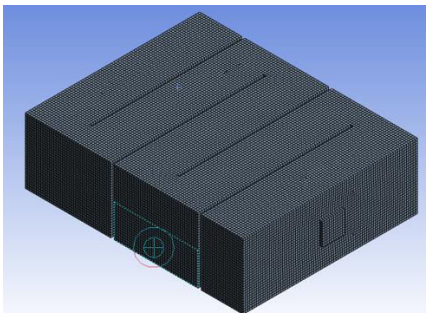


Fig. 7. Meshed model of air-filtration-plants-zigzag-panels

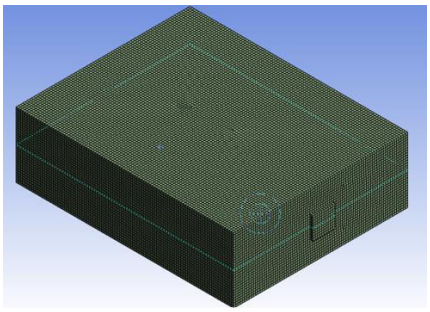


Fig. 8. Meshed model of Air-filtration-Plants-parallel panels-mesh

2.3. Physical and Numerical Modelling

After preparing the numerical model for CFD analysis, The CFD simulation was conducted in ANSYS FLUENT 21 by assuming incompressible flow and by considering pressure-based solver for steady state flow. In addition to this, the process of filtration via plant-based filter panel of PM_{10} particles was enabled through modelling of air as major continuous phase within the multiphase Eulerian framework. During the CFD simulation k–ε model was utilized for simulation of airflow in turbulent mode. Table 2 shows the pretties of air used in modelling of air for CFD analysis. In order to consider the effect of temperature, energy equations were also included.

Table 1. Properties of air for CFD simulation

Sr.	Properties of air	Magnitude/value
1.	Density	1.225 kg/m³
2.	Dynamic Viscosity	1.7894×10^{-5} kg/m·s,
3.	Thermal Conductivity	0.0242 W/m·K
4.	AQI	90
5.	Initial PM_{10} concentration	80 µg/m³

2.4. Boundary Conditions

In the present analysis through CFD simulation of different configuration of plant(panel) based filtration system four different initial velocities of 0.5,.01,.5, and 2.0 m/s were employed to study its effect upon on output field variables. During the all cases of CFD simulation, atmospheric conditions i.e. 298.15 K (25°C) pressure at 101325 Pa were considered at outlet as inlet temperature and initial pressure respectively. Besides this, diameter of hydraulic opening was taken as 0.1m at both inlet and outlet with an intensity of turbulence of 5% was applied. Besides this a gauge pressure of 0 Pa was imposed at outlet for ensuring discharge of air in smooth form. Table 2 gives the different boundary conditions used in all cases of CFD analysis, which shows that AQI, inlet conditions, initial velocity of air, PM_{10} particles concentrations for all three different configurations.

Table 2. Boundary conditions used in CFD analysis

Sr	Plant Configuration	AQI	PM_{10} ($\mu g/m^3$)	PM_{10} (kg/m^3)	Inlet Velocity (m/s)	Inlet Temperature (K)
1.	Blocking Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15
2.	Zigzag Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15
3.	Parallel Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15

2.5. Numerical Solution and Post-Processing Analysis

In the present analysis the governing partial differential equations for mass, momentum, energy, and turbulence were based on Finite element Volume scheme in conjunction with pressure-velocity coupling based on SIMPLE algorithm. The discretization schemes utilized are as follows: body-force weighted for pressure, second-order upwind for momentum and energy, and first-order upwind for turbulent kinetic energy (k) and dissipation rate (ε). Hybrid initialization was implemented, and simulations were conducted for up to 1000 iterations or until residuals decreased below 10^{-6}, thereby confirming convergence. After CFD simulation the ANSYS Fluent gives the field variables in terms of the contour plots of air velocity, velocity of PM_{10} particles and velocity vector trajectories with the domain of filtration plant for all three configurations.

3. RESULTS & DISCUSSION

3.1 Air velocity distribution for different strategies/models for air pollution treatment

Figure 9-20 shows the effect of inlet air velocity upon the velocity of air as field output variable for different configurations of plant-based filtration systems such as blocking, parallel and zigzag. It was gathered that the output field variable i.e., dependent upon input variables such as inlet velocity of air, types of panels and geometry of the air plantation chamber. All these parameters assess the strength of recirculation of air, dispersion of air across the chamber for uniformity and contact of air and surface for filtration purpose.

Contour plots of velocity of the blocking panels configuration were depicted in figures 9-12, which shows the variation of intensities across the chamber for four different inlet velocities of air. It was clear from the contour plots (figures 9-12) that greatest velocity of air appeared near inlet and outlet of the chamber, which was attributed to pressure difference. In addition to this, it was also gathered that minimum velocity of air was seen in the central zones of chamber which in turn produced recirculation of air before the blocking panels and further this has yielded in increment in greater residence time and better air to surface interaction for filtration purpose. Besides it was also realized that increment in inlet velocity of air from 0.68 m/s to 2.77 m/s resulted in more pronounced uniform distribution of air due to intensified air flow, but it still there is some zones of stagnations that were situated behind the blocking panels having low velocities. It was clear that blocking panels significantly resisted the air flow and lowered the filtration effect due to non-uniformity of air flow.

On the contrary, figures 13-16 shows the contour plots of velocity throughout the rectangular chamber for parallel configurations of plant-based filtration systems. It was clear from these figures that for parallel arrangement the air flow majorly through the central route and replicating a streamlined patterns and offers resistance in moderate manner. It was also gathered for parallel configurations, that at lower inlet velocities in the range from 0.5m/s -1.0 m/s distribution of velocity remains nearly smooth but the interaction of air to surface is minimum near the sidewalls. It was cited that as the velocity of air increases beyond 1.0 m/s, it results in a significant filtration effect. Besides these, zones of stagnation with low velocities were also observed, which can be overcome by improvement in designs and, in turn, resulted in better filtration efficiency. In another case, the air filtration plant's zigzag configuration resulted in the highest dispersion of air, as shown in figures 17-20. In all cases, the zigzag configuration resulted in better filtration as compared to the other two cases, which can be attributed to higher air-to-surface interaction.

It was seen that at lower intensities of inlet air velocity (0.5-1.0 m/s), the air moved smoothly across the channel, but upon increment in inlet air velocity in the range of 1.5-2.0 m/s has resulted in zones of accelerated airflow near the bending zones and resulted in moderate recirculation of air behind these panels. Figure 20 shows the maximum speed of 2.79 m/s, demonstrating better mixing and momentum transmission, but it also displays a small amount of unevenness close to the panel boundaries. Based on these observations, it was found that zigzag configuration brought better redistribution and higher time of residence in comparison to blocking and parallel panels arrangement. Hence zigzag panels arrangement found to be most effective in uniformity of flow, enhanced mixing, and filtration effect as compared to parallel and blocking configurations.

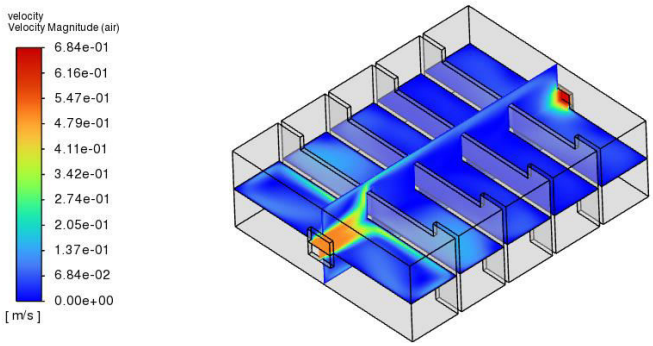


Fig. 9. Air-filtration-Plants-Blocking panels-v-0.5-velocity contour

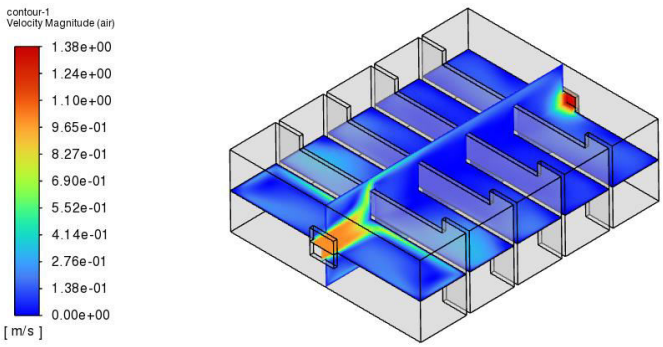


Fig. 10. Air-filtration-Plants-Blocking panels-v-1-velocity contour

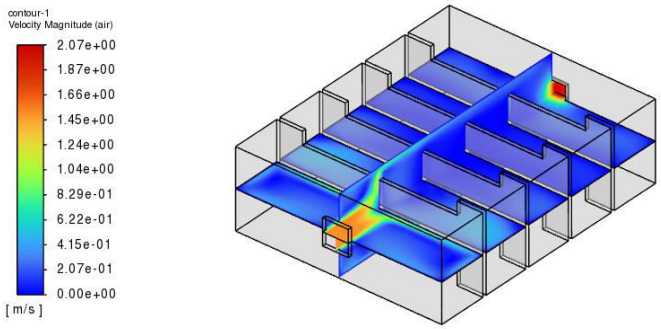


Fig. 11. Air-filtration-Plants-Blocking panels-v-1.5-velocity contour

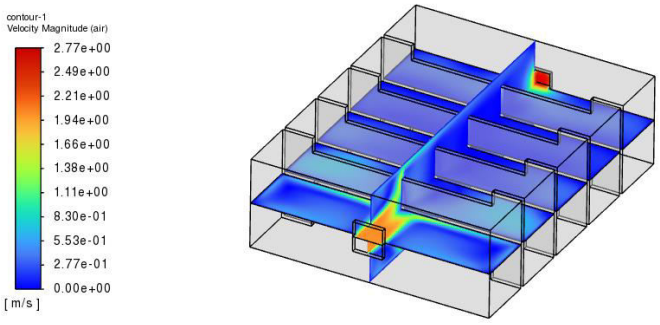


Fig. 12. Air-filtration-Plants-Blocking panels-v-2-velocity contour

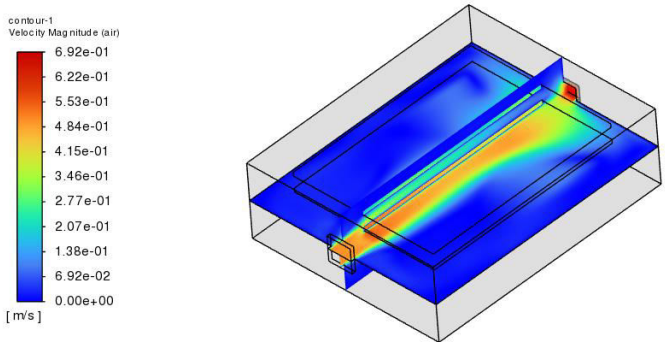


Fig. 13. Air-filtration-Plants-parallel panels-v-0.5-velocity contour

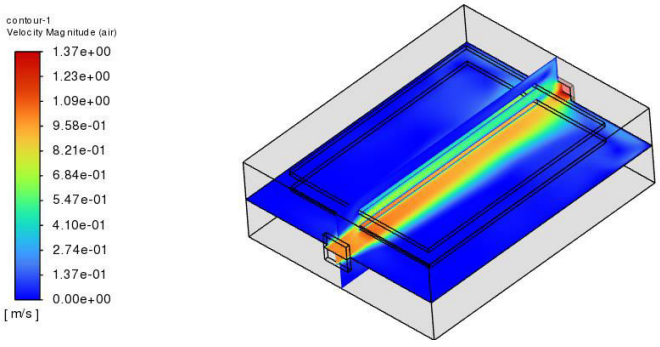


Fig. 14. Air-filtration-Plants-parallel panels-v-1-velocity contour

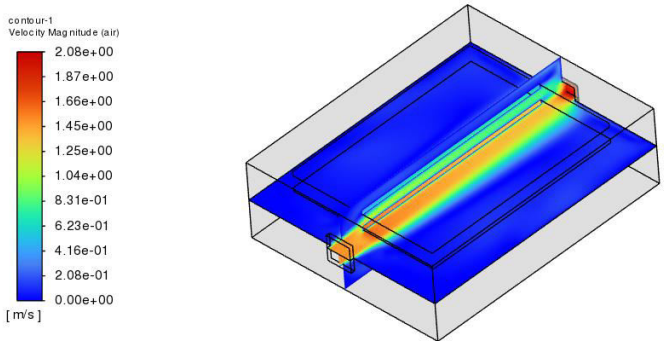


Fig. 15. Air-filtration-Plants-parallel panels-v-1.5-velocity contour

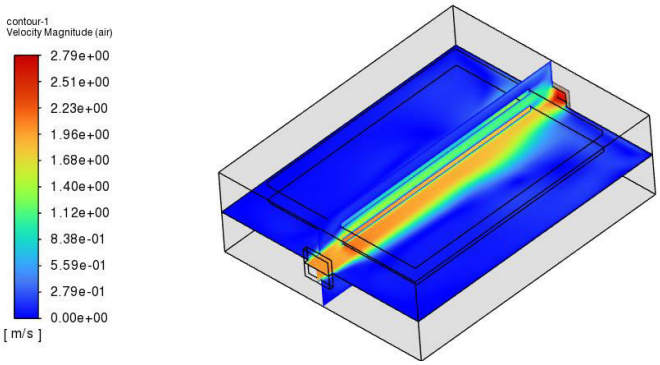


Fig. 16. Air-filtration-Plants-parallel panels-v-2.0-velocity contour

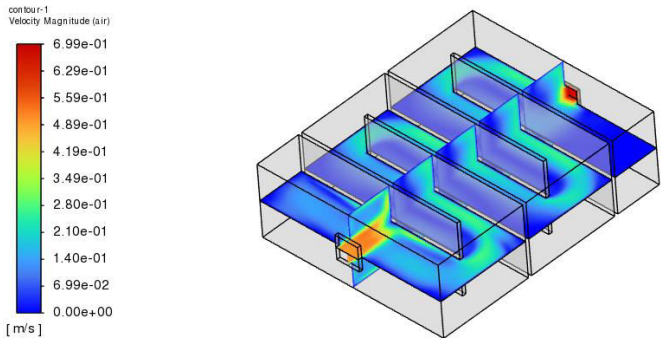


Fig. 17. Air-filteration-Plants-zigzag-panels-v-.5-velocity contour

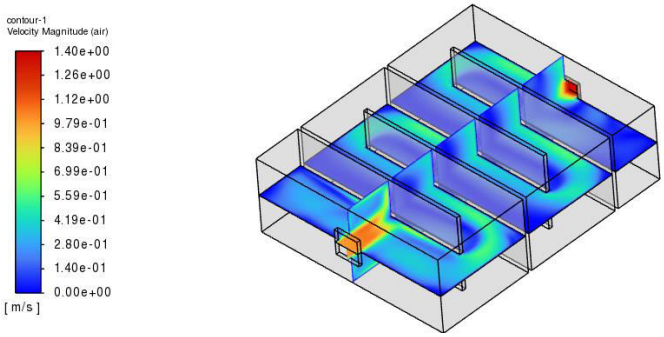


Fig. 18. Air-filteration-Plants-zigzag-panels-v-1-velocity contour

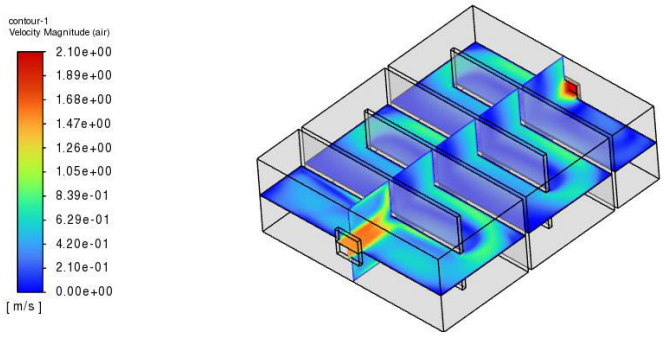


Fig. 19. Air-filteration-Plants-zigzag-panels-v-1.5-velocity contour

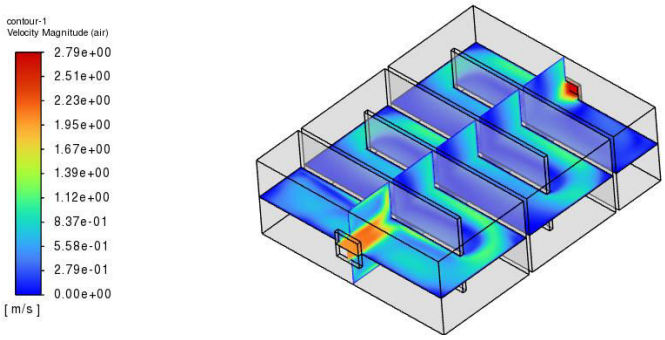


Fig. 20. Air-filteration-Plants-zigzag-panels-v-2-velocity contour

3.2 PM_{10} velocity distribution of different models for air pollution treatment

Figures 21 to 32 depicted the effect of inlet velocity (0.5 m/s to 2.0 m/s) on PM_{10} velocity distribution for all three configurations of air-filtration panels namely blocking, parallel and zigzag. Figure 21 to 24 shown the distribution of velocity for blocking panel configuration which ranges from 0-2.89 m/s. Figure 21 shows the contour plot of velocity distribution at inlet velocity of 0.5 m/s for blocking configuration which indicated that there is generation of stagnation behind the panels due to complete blockage of air which resulted in longer residence time with reduced overall uniformity of flow. It is also clear from figure 22 and 23 that upon increment of inlet velocity of air from 1.0 m/s to 1.5 m/s there is increment in turbulence and flow becomes continuous as compared to lower inlet velocities, but it still includes localized recirculation behind blocking configurations. In addition to this, figure 24 illustrated a strong jet-like flow and turbulence which resulted in more mixing during air flow and transportation of pollutants.

Although in this situation could raise pressure drop and stress on plant surfaces. Overall, the blocking structure offered a high potential for particle capture due to greater retention time, but i t sacrificed flow homogeneity and energy efficiency.

Figures 25 to 28 shows the velocity of PM_{10} particles for the parallel configurations which shown that airflow followed majorly central zone of the chamber in linear fashion. It was noticed that as the inlet velocity of air from 0.5 m/s to 2.0 m/s, maximum velocity increased from 0.67 to 2.59 m/s. It was gathered from figure 25 and figure 26 that at lower velocities, minimum turbulence with little interaction with plant surfaces was observed, which indicated flow was smooth and laminar. On the other hand, it can be seen from figure 27 and figure 28 which corresponds to inlet velocity of 1.5 m/s and 2. 0 m/s, upon increment of velocity has increased the turbulence and gradient of velocity which eventually resulted in more improved transport of particles and better interaction with the plants, but it includes zones of low velocities near the walls as well. In summary, the parallel structure produced the most uniform and energy-efficient airflow, but with lesser mixing and particle capture due to the shorter residence period.

Figures 29 to 32 shows the contour plots of air velocity which shows the flow in zigzag manner created turbulence and better particle dispersion due to change in direction in readily form. Figure 29 shows the distribution of air velocity; flow remains slow and in recirculated manner which created improved time of residence and deposition of particulate. Figure 30 and 31 shows the contour plots for 1 m/s and 1.5 m/s the air flow becomes distributed in uniform form with balanced turbulence. Figure 31 shows more pronounced mixing with ample amount of PM_{10} capture. It was found from figure 32 that for velocity of 2.0 m/s, resulted in greatest velocity of 3.27 m/s which in turn resulted in enhanced dispersion with decreased time of residence with some higher loss of pressure.

In nutshell panels in blocking configuration increased deposition of particles via stagnation with low homogeneity of air flow. The parallel arrangement provides smoother and more energy-efficient flow with little contact. The zigzag shape achieves the optimal balance of mixing, turbulence, and residence time. As a result, for vegetation-based air-filter systems, a zigzag design with moderate inflow velocities of 1.0 to 1.5 m/s provides the optimal mix of filtration efficiency, air distribution, and energy performance.

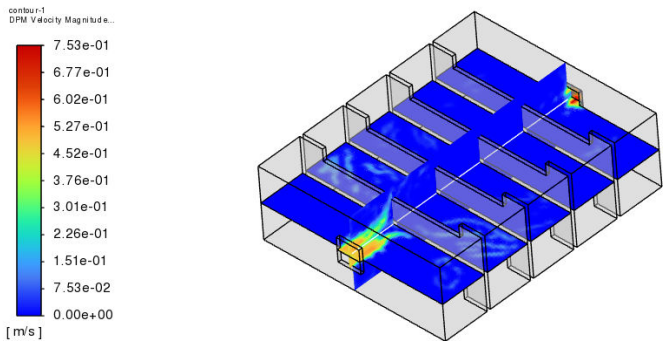


Fig. 21. Air-filtration-Plants-Blocking panels-v-0.5-pm10-velocity contour

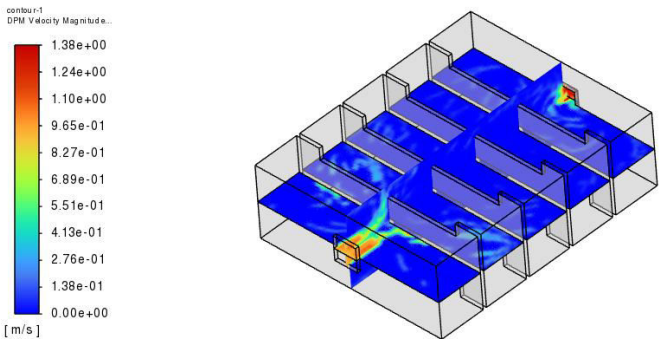


Fig. 22. Air-filtration-Plants-Blocking panels-v-1-pm10-velocity contour

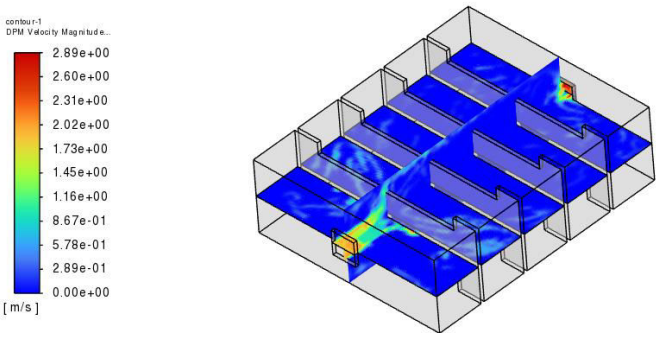


Fig. 23. Air-filtration-Plants-Blocking panels-v-1.5-pm10-velocity contour

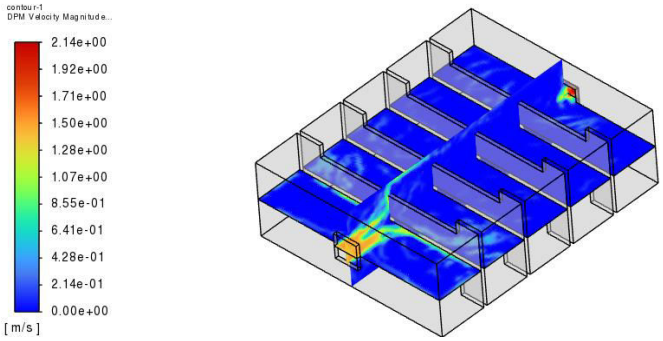


Fig. 24. Air-filtration-Plants-Blocking panels-v-2-pm10-velocity contour

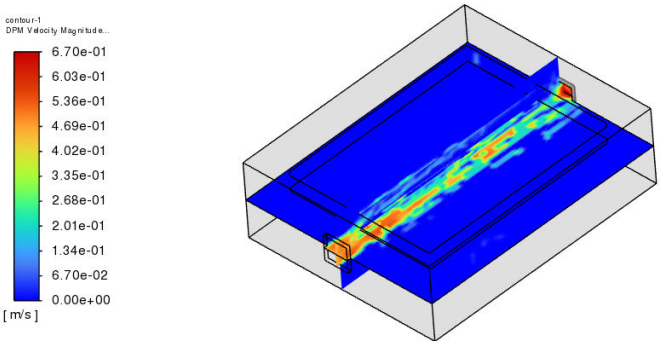


Fig. 25. Air-filtration-Plants-parallel panels-v-0.5-pm10-velocity contour

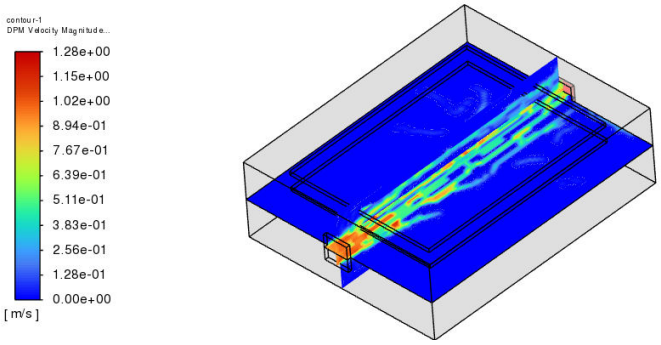


Fig. 26. Air-filtration-Plants-parallel panels-v-1-pm10-velocity contour

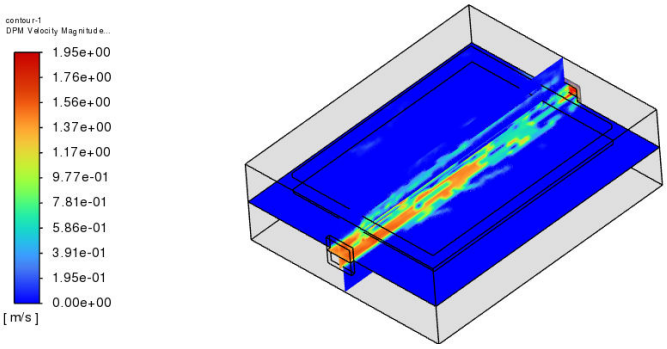


Fig. 27. Air-filtration-Plants-parallel panels-v-1.5-pm10-velocity contour

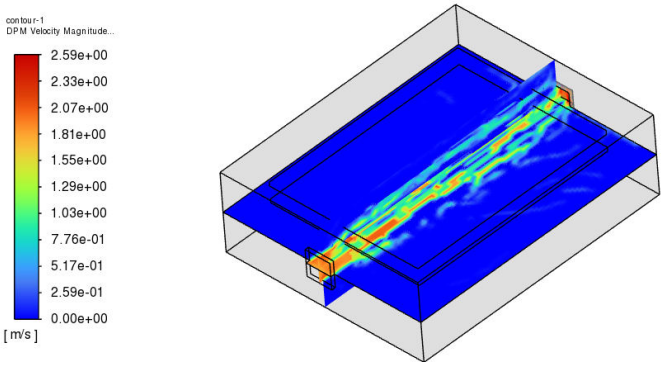


Fig. 28. Air-filtration-Plants-parallel panels-v-2-pm10-velocity contour

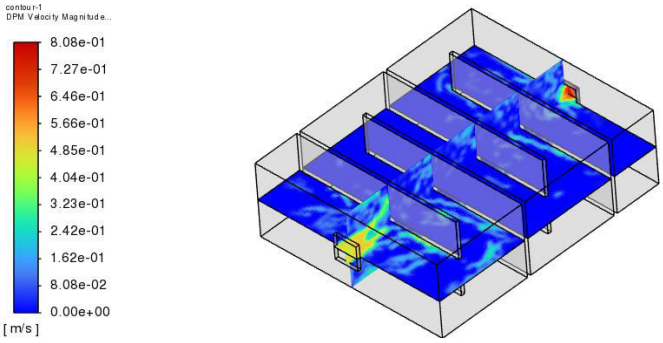


Fig. 29. Air-filteration-Plants-zigzag-panels-v-.5-pm10-velocity contour

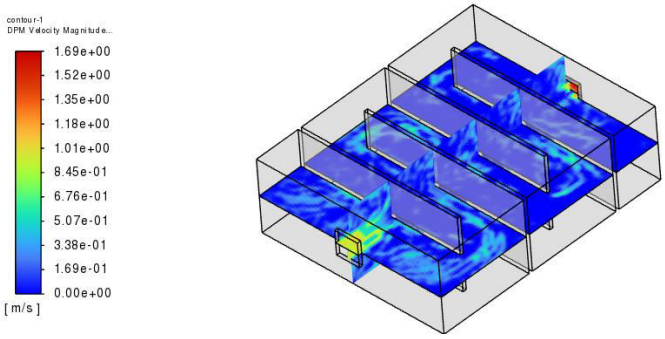


Fig. 30. Air-filteration-Plants-zigzag-panels-v-1-pm10-velocity contour

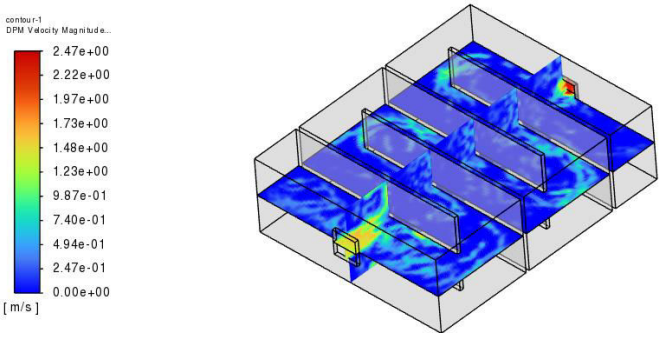


Fig. 31. Air-filteration-Plants-zigzag-panels-v-1.5-pm10-velocity contour

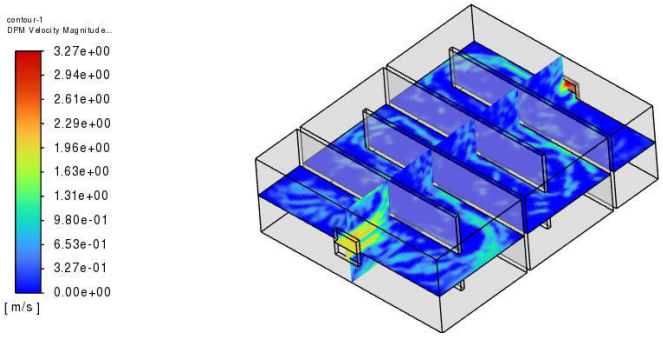


Fig. 32. Air-filteration-Plants-zigzag-panels-v-2-pm10-velocity contour

3.3 Effect of air velocity on field variables for different models

Figures 33 to 41 show the airflow and particle behavior in plant-based filtration systems with different plant arrangements, including blocking, zigzag, and parallel to airflow, at varying inlet velocities (0.5–2.0 m/s). An increment in average air velocity with inlet velocity, which was seen from Figures 33-37, ensured stability in aerodynamic response. It was observed that for the zigzag case, peak velocities are obtained at all planes, which resulted in the best mixing and lowest stagnation zones, which can be attributed to zigzag paths. On the other hand, moderate configuration and moderate velocity with less turbulence and a blocking configuration experienced the greatest resistance and the lowest velocity of air. In a summarized manner, it was gathered that the zigzag configuration is the best out of all three cases due to the best air circulation velocity and maximum filtration.

Figures 38-39 show the PM_{10} mass flow rate for all three configurations. It was gathered that the PM10 mass flow rate at the outlet is lowest for zigzag due to the highest turbulence, intermediate for parallel, and maximum for the blocking configuration. On the other hand, figures 40-41 show that the inside air temperature increases with increments in air inlet velocity. Slightly higher air temperature was recorded for the zigzag configuration as compared to the other two cases, which can be attributed to better mixing of air via convection, higher turbulence, and superior filtration effect.

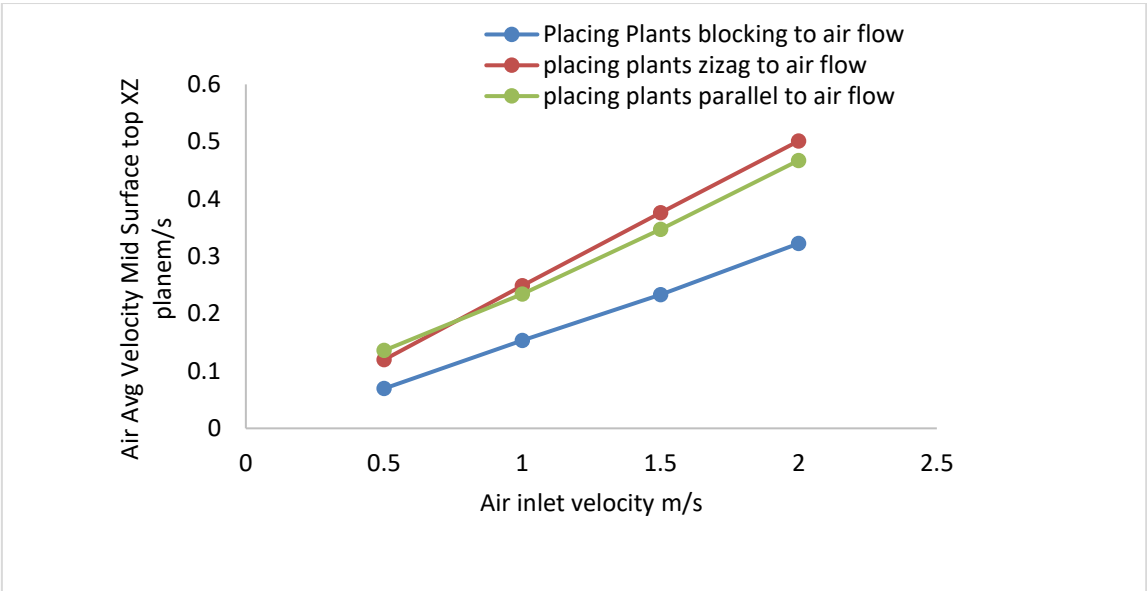


Fig. 33. Air Average velocity at Mid Surface Top (XZ plane) Vs Air Inlet Velocity

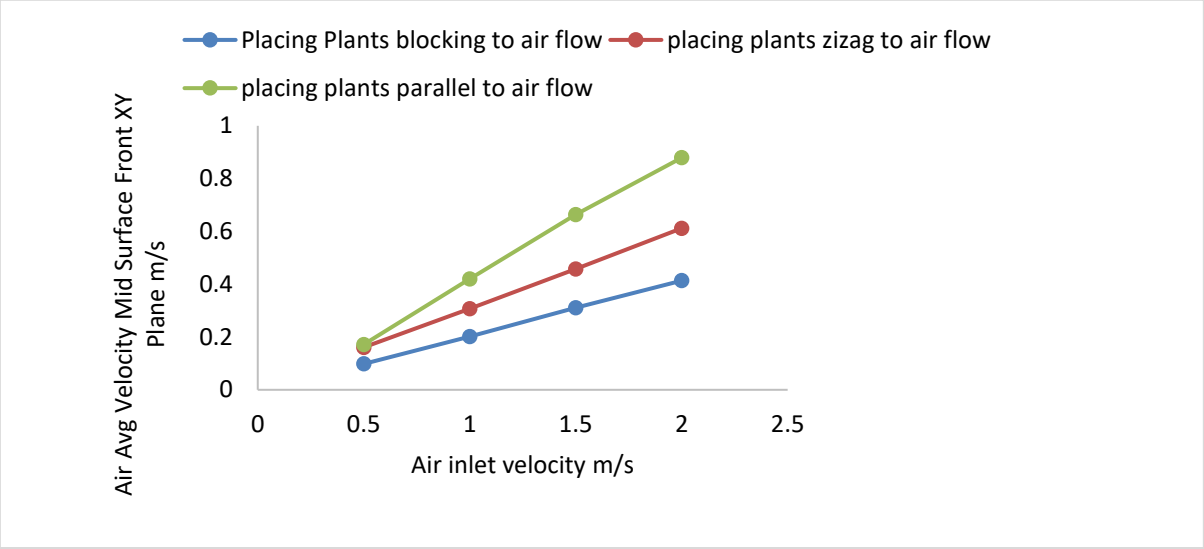


Fig. 34. Air Average velocity at Mid Surface flow Front (XY Plane) Vs Air Inlet Velocity

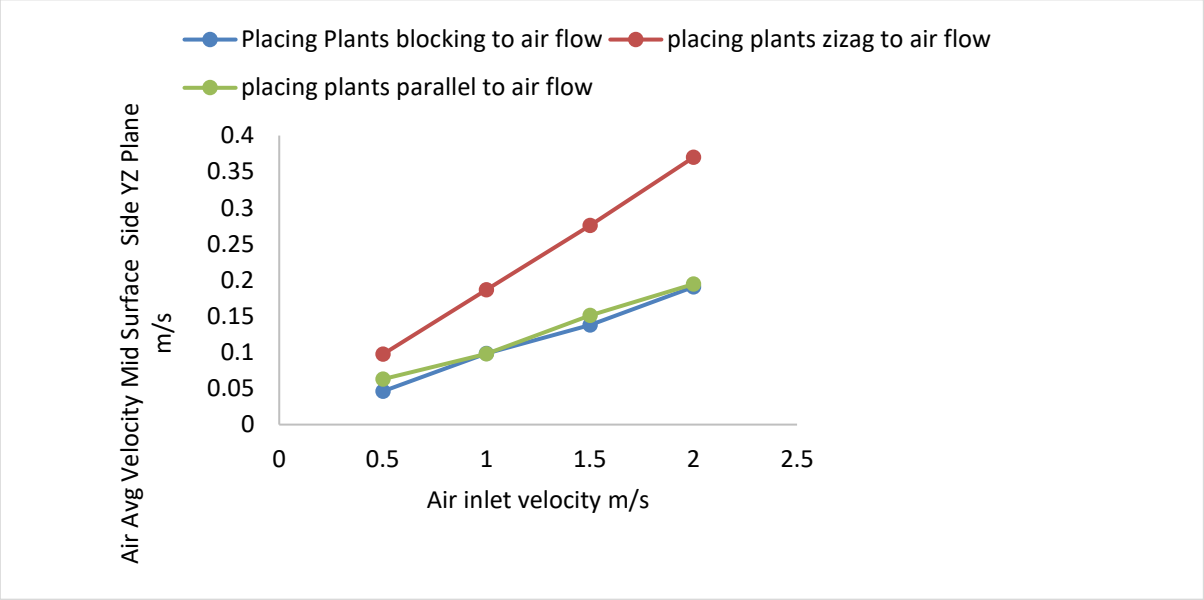


Fig. 35. Air Average velocity at Mid Surface Side (YZ plane) Vs Air Inlet Velocity

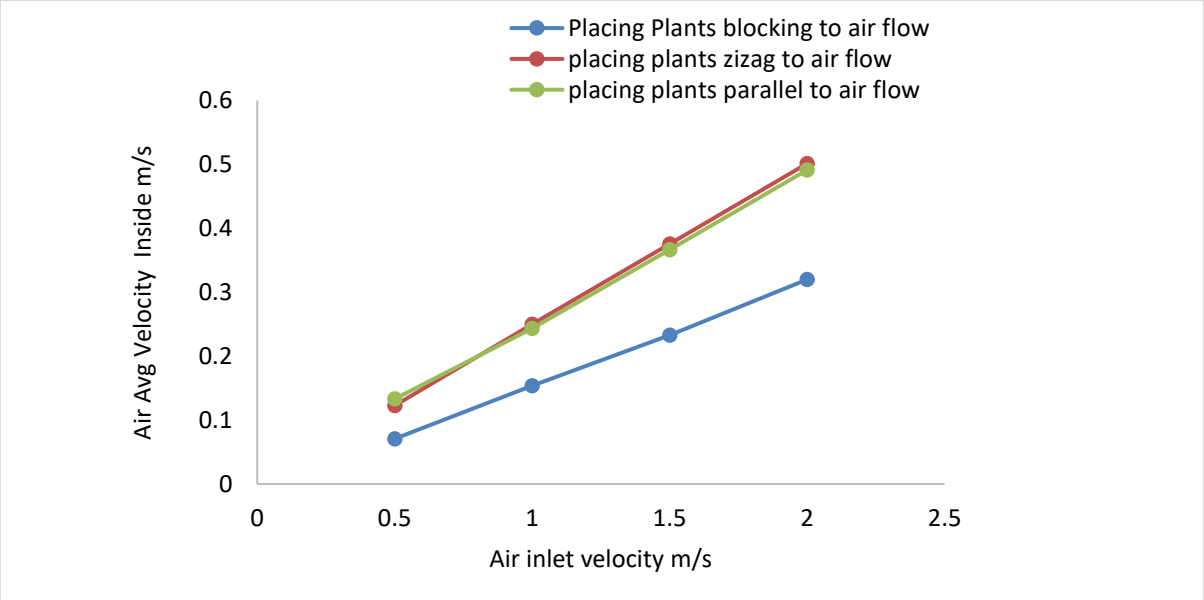


Fig. 36. Air Average velocity inside Vs Air Inlet Velocity

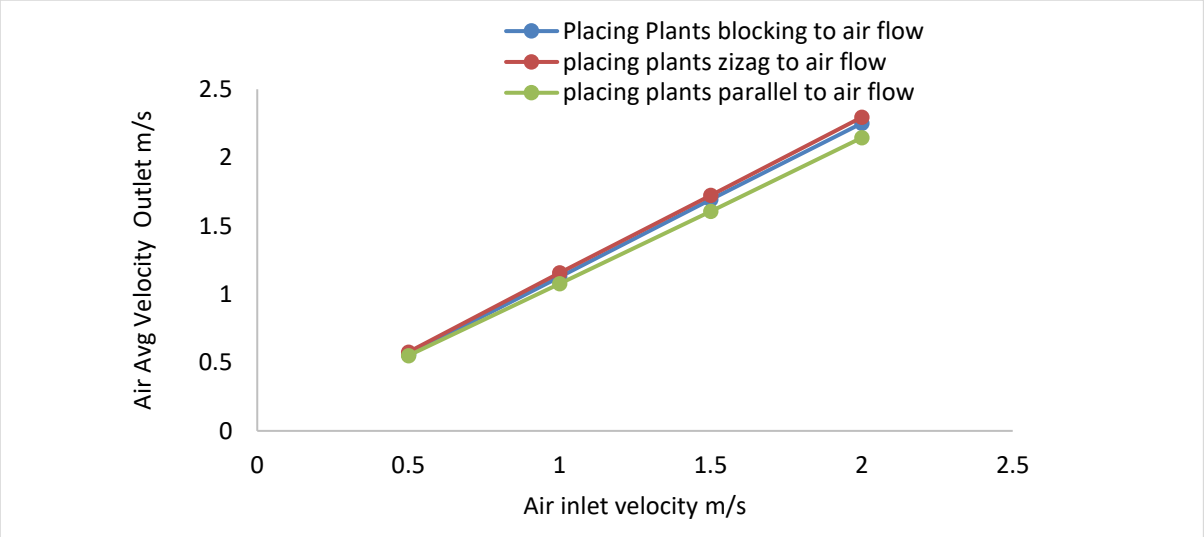


Fig. 37. Air Average velocity outlet Vs Air Inlet Velocity

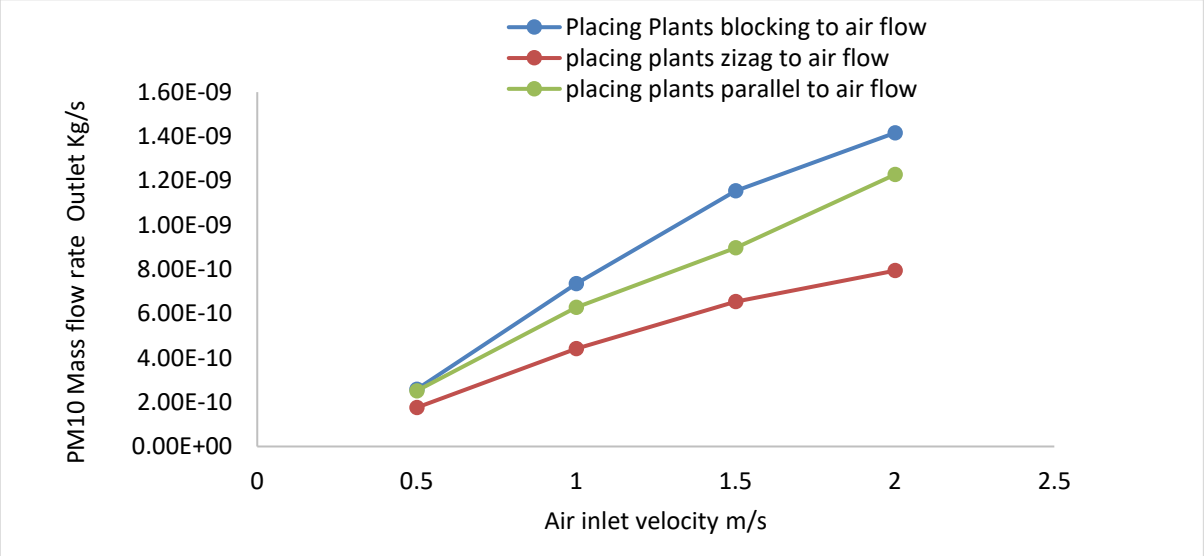


Fig. 38. PM 10 Mass flow Rate kg/s at outlet Vs Air Inlet Velocity

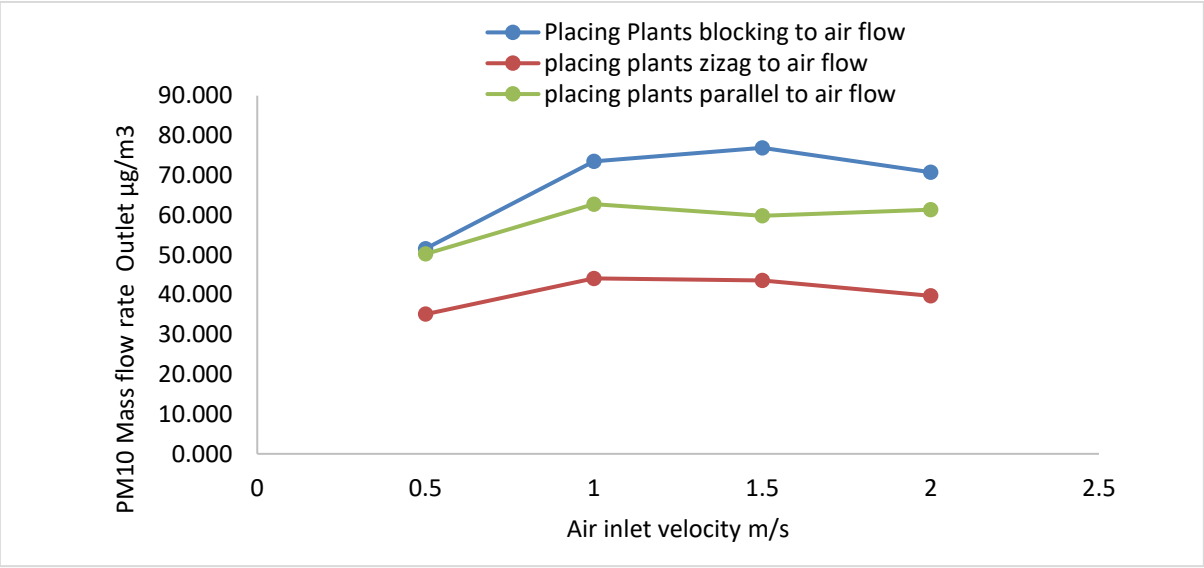


Fig. 39. PM 10 Mass flow Rate µg/m3 at outlet Vs Air Inlet Velocity

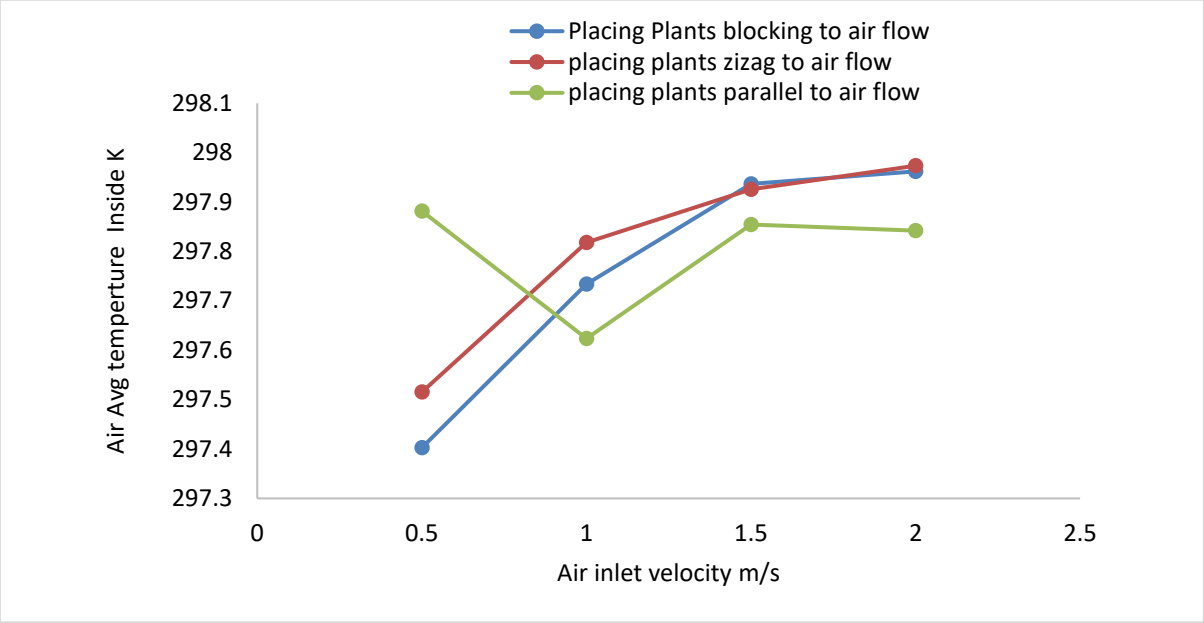


Fig. 40. Air Average Temperature inside Vs Air Inlet Velocity

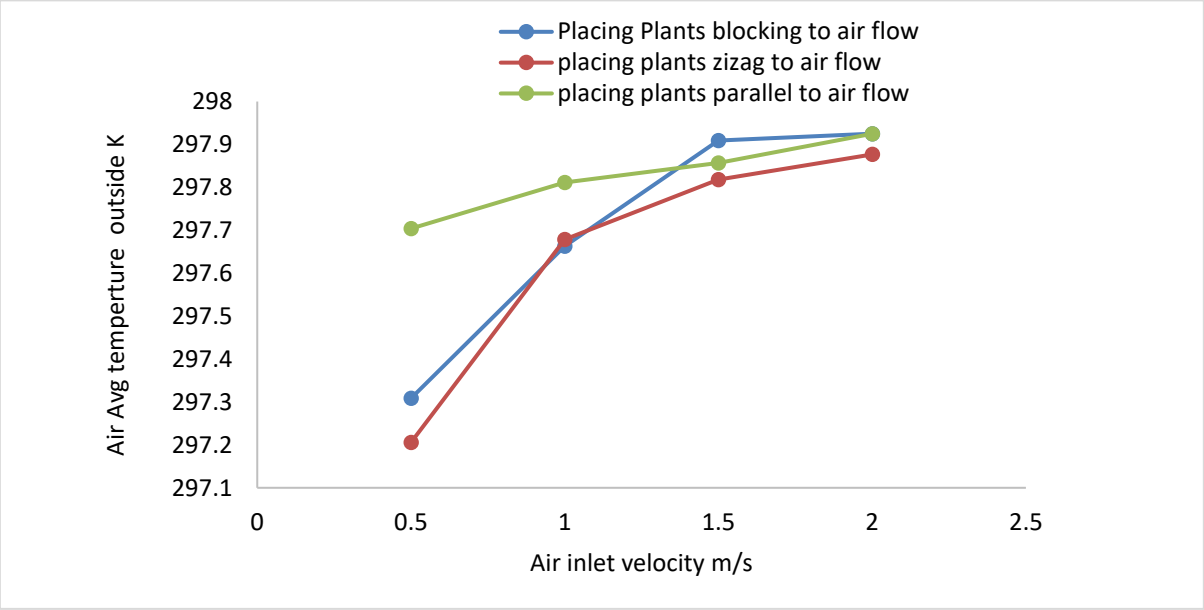


Fig. 41. Air Average Temperature Outlet Vs Air Inlet Velocity

3.4 Distribution of Velocity vectors of different models

Figures 42 ,43 and 44 show the velocity vector contours for three types of plant-based air filtration setups: blocking, parallel, and zigzag panels. In the blocking panel setup (Figure 42), the airflow faces strong resistance when it hits the front plant surfaces. In case of blocking configuration, due to arrangement of panels air gets blocked and zones of stagnation were visualized along with recirculation and resulted in poor air filtration least of all cases. It was seen from figure 43 that for parallel configuration, better air flow was obtained with high velocity in the center and lower velocity at zones near plant surfaces which resulted in better filtration effect than blocking. On the contrary figure 44 shows the zigzag configuration in which most filtration effect is obtained as compared to all cases which can be attributed to presence of alternate zones of high and low velocities with better turbulence for achievement of air filtration.

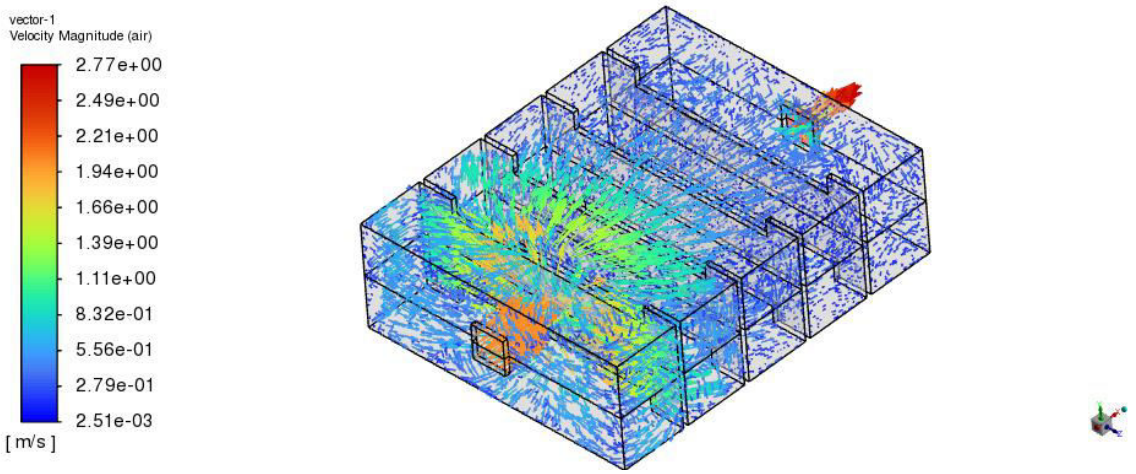


Fig. 42. Air-filtration-Plants-Blocking panels-v-2-vel-vector-velocity contour

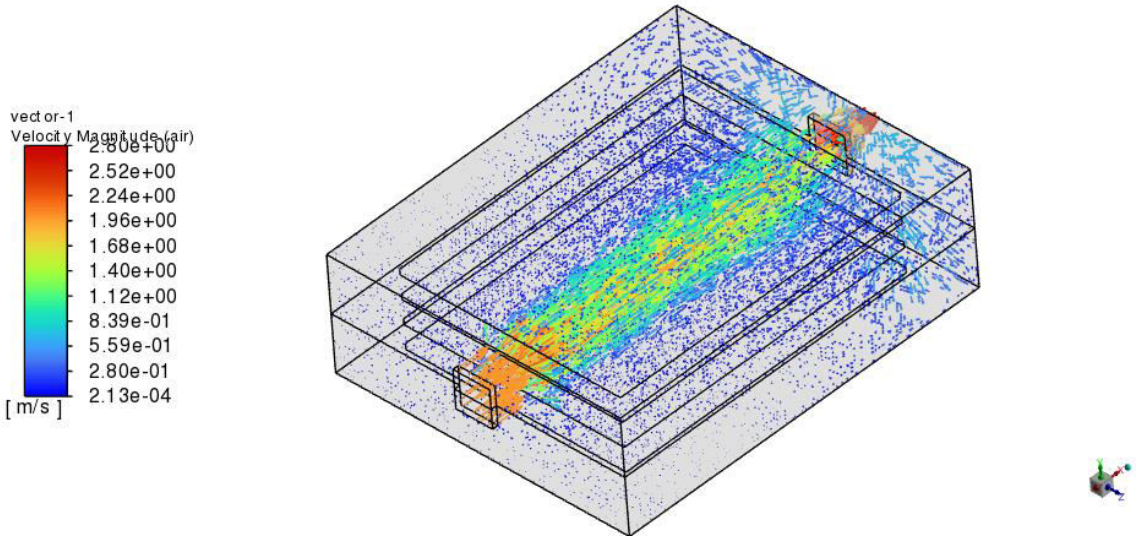


Fig. 43. Air-filtration-Plants-parallel panels-v-2-vel-vector-velocity contour

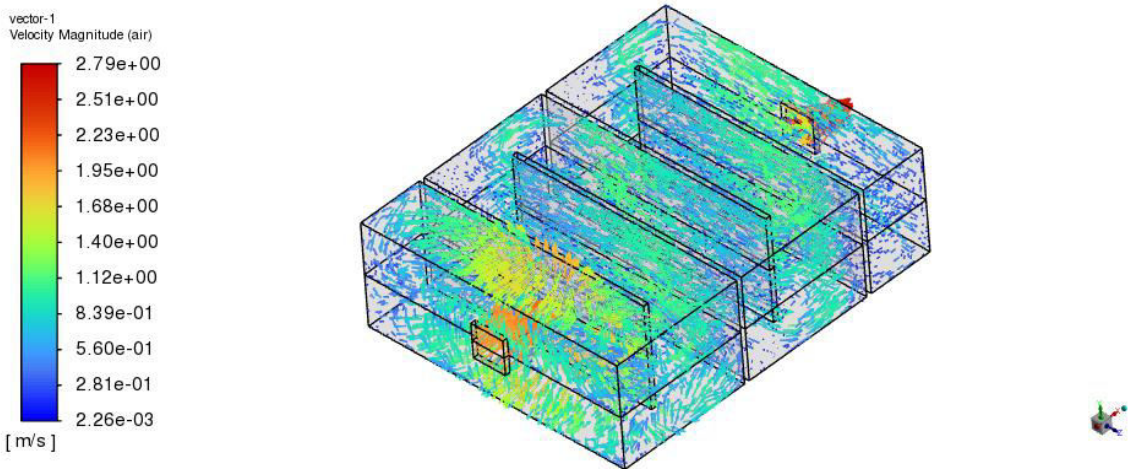


Fig. 44. Air-filteration-Plants-zigzag-panels-v-2-vel-vector-velocity contour

4. Conclusions

The present research work focuses on the three-dimensional CFD simulation of plant-based panels for air purification and pollutant removal. Three different types of plant-based panels, namely blocking, parallel, and zigzag layouts, have been utilized within the velocity ranges of 0.5-2 m/s for the investigation of airflow patterns and filtration effect. It was found through CFD simulation that both airflow characteristics and maximum removal of PM10 particles were recorded as compared to the other two configurations due to alternative geometrical paths of air-flow and maximum turbulence. On the other hand, intermediate better flow, and removal of PM10 particles were found in the case of parallel layouts. The least turbulence in air flow and minimum removal of PM10 particles were observed for the blocking configuration due to its geometry. Besides this, the optimal performance of the zigzag configuration for efficient air-flow and maximum pollutant removal occurred in a range of 1-1.5 m/s. Hence, out of all three types of plant panels zigzag configuration was found to be the most applicable design for plant air filtration systems due to the application of plant-based filters. The following are the major concluding remarks that emerged from this CFD analysis:

i. The zigzag panel configuration produced the best-mixed airflow, with alternating high and low velocity regions, and the lowest outlet PM_{10}, showing effective particulate capture.
ii. Blocking panels led to a strong slowing of airflow and large recirculation areas behind the plants, increasing residence time but creating dead zones and resulting in poor filtration effect of PM10 particles.
iii. Uniform and minimum resistance flow and minimum turbulence were obtained in the case of the parallel configuration due to flow in a straight line, and only a moderate filtration rate was obtained.
iv. An optimal velocity range of inlet air velocity from 1-1.5 m/s was obtained for all cases since it increases better mixing and increased flow rates.
v. Zigzag panels emerged as the best plant panel for air filtration work out of all cases since it has secured the best filtration performance and as well as managed pollutant removal rate.

Acknowledgement

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3

An Analysis of Solar Modulation of Cosmic Rays and Their Significance on Earth's Climate

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Abstract

Earth receives markedly higher solar irradiance during periods of high solar activity than during quiet conditions, and this variation has been considered here to study its bearing on galactic cosmic rays (GCRs) and, in turn, on climate. GCRs, being high-energy charged particles, get modulated by the heliospheric magnetic field carried outward by the solar wind, giving rise to the well-known anti-correlation, seen in neutron monitor data, between cosmic ray intensity and solar activity indices such as sunspot number, following an approximately 11-year cycle corresponding to half of the solar magnetic cycle. Modulation processes differ for positively and negatively charged particles and also vary with solar magnetic polarity. Here, the effects of outward and inward heliospheric field configurations, and of both solar magnetic polarities, on cosmic ray modulation have been examined, drawing on a literature-based synthesis of publicly archived solar, cosmic ray, and climate datasets, viz. WDC-SILSO, NMDB, and standard instrumental temperature compilations. Modulation of the terrestrial cosmic ray flux is considered as a possible solar influence on climate, acting through atmospheric ion production and electrical conductivity. Cloud nucleation associated with cosmic ray flux is also discussed, along with the balancing evidence from CERN's CLOUD experiment, which indicates that the amplification mechanism linking microphysical effects to macroscopic climate response is, at best, only partly quantified. Daily and monthly sunspot numbers over approximately two centuries are analysed, together with the open solar magnetic flux and the 6–12-month lag observed between solar and cosmic ray variability. The correlation between sunspot number and global surface temperature (GST) is found to lie in the range $r \approx 0.5$-0.7 for the pre-1980 record, weakening markedly thereafter, consistent with a growing dominance of greenhouse-gas forcing. The results, taken together, contribute to a more balanced understanding of the possible role of solar-modulated cosmic rays in climate variability.

Keywords

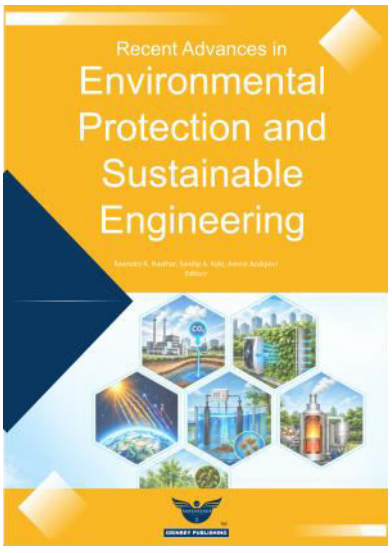
Solar Modulation; GCR; Heliospheric Magnetic Field; Sunspot Number; Climate Variability

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1. Introduction

The Sun is the main driver of all energy on Earth. The atmosphere surrounding Earth becomes turbulent because of the Sun's heat. The energy fluctuates over an 11-year cycle [1-4]. The total energy that reaches Earth during this cycle shifts by about 0.1%. During solar cycles, the Sun's energy gradually shifts. There are times when the Sun is more active. The lower atmosphere is warmed by ozone reactions. These reactions are brought on by intense UV radiation. The air at the North and South Poles is heated by geomagnetic activity. More sunlight can reach the ground when there are fewer clouds. This decrease in clouds is caused by fewer cosmic rays. The Earth heats up significantly in these minor alterations. Both short- and long-term climate conditions can be influenced by the Sun. On time scales ranging from 28 days to 12, 23, 81, 181 years, and beyond, the Sun's activity varies. Because it dominates the cooler sunspots, an active Sun is brighter. During solar maxima, our planet receives more radiation from the Sun than it does during solar minima. Earth's climate change is largely caused by a variety of indirect factors, including these radiative effects of solar variation. Monitoring eruptional activity over a specific time period has been shown to be essential for measuring solar irradiance.

2. Data sources and analytical approach

This study is based on a comparative, literature-informed analysis of publicly archived solar-terrestrial datasets rather than newly acquired observations. Daily and monthly sunspot numbers spanning approximately two centuries (1818-2020) were drawn from the World Data Center for the Sunspot Index and Long-term Solar Observations (WDC-SILSO), Royal Observatory of Belgium [5]. Cosmic ray intensity records were obtained from ground-based neutron monitor stations archived in the Neutron Monitor Database (NMDB) [6], and open solar magnetic flux estimates followed the reconstruction methodology of Lockwood et al. [2]. Global surface temperature (GST) anomalies, likewise, have been taken from standard instrumental compilations, viz. the Berkeley Earth record and the IPCC Sixth Assessment Report [7, 8]. The analysis, in essence, is a qualitative and semi-quantitative comparison of the temporal profiles of these several series - sunspot number, neutron monitor count rate, open solar flux and GST - over common time windows, and it is supplemented by correlation and lag estimates already reported in the cited literature rather than by any fresh statistical re-analysis of the raw series. Since the study synthesizes and cross-compares existing published records instead of presenting new experimental measurements, its principal contribution lies in bringing together, within a single framework, the observational evidence for solar-cosmic ray-climate coupling, and in pointing out the quantitative gaps - such as the lag between solar and cosmic ray variability and the strength of the sunspot-GST correlation - that are taken up numerically in Sections 6 and 7.

3. Heliospheric Propagation and Modulation of GCR

High-energy charged cosmic ray nuclei, present throughout interstellar space, are continually approaching the inner Solar System. The Sun, however, provides a natural defence against them: it continuously throws out a stream of ionized plasma, viz. the solar wind, and this forms a protective magnetic barrier around the heliosphere. This wind carries its own magnetic field; it creates a turbulent barrier that cosmic rays must fight to cross. Only the most energetic particles can successfully navigate this magnetic obstacle to enter the inner Solar System. As the ionized material expands away from the Sun, this intricate magnetic field structure stays "frozen" within it [9, 10]. According to research, solar wind particles near Earth have a mean kinetic energy of 600 MeV and range in velocity from 260 to 650 km/s. The mean interplanetary magnetic field strength near Earth is separately estimated at approximately 3-5 nT (~3×10^{-5}-5×10^{-5} G) [11]; being a distinct physical quantity governed by different physics, it is not directly comparable in magnitude to the particles' kinetic energy. Neutron monitor data and the Sun's sunspot numbers show an anti-correlation when

the solar system modulates galactic cosmic ray particles [12, 13]. Following an 11-year solar period - exactly 50% of the Sun's complete magnetic cycle - the sunspot number designates the solar active regions. Changes in the sunspot number are observed to occur one to two years later. Areas of outward and inward magnetic polarity are divided by the current sheet. This sheet is produced by a combination of the solar wind's radial flow and solar rotation. These inward (b) and outward (a) magnetic fields are shown in Figure 1.

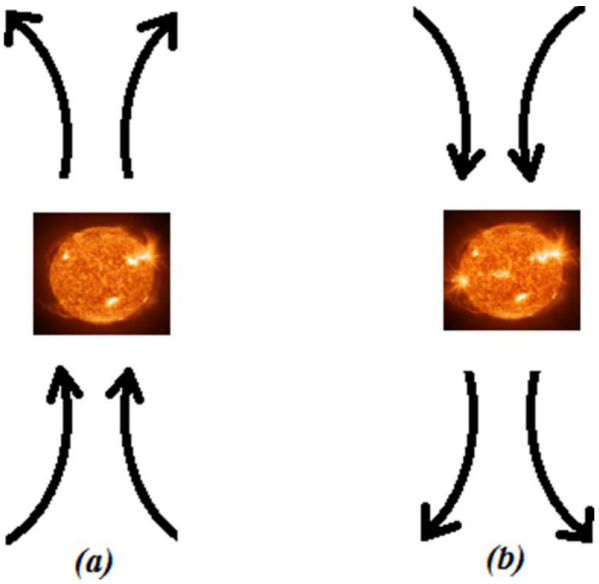


Fig.1. Magnetic field directed away (+ve polarity), (b) Magnetic field directed in (-ve polarity)

There is evidence that, depending on solar polarity, both positively and negatively charged particles modulate through different mechanisms. One important finding is that the profile of neutron monitor data varies depending on the solar magnetic state [11, 12]. The field lines of the Sun's magnetic field impose particular characteristics on the interplanetary field during different solar polarities. Cosmic ray particles typically revolve around the solar system's magnetic field lines. Nonetheless, these field lines are perpendicular to efficient transport. An electron or antiproton are examples of negatively charged particles that drift in the opposite direction of positively charged particles. The particle's drift direction changes in tandem with the reversal of solar polarity. The current sheet is not a one-dimensional plane in practical application; particle motion is extremely complicated. This sheet's wavy structure affects the particle's path across the heliosphere. The behaviour of the solar environment during (a) North-seeking solar polarity and (b) South-seeking solar polarity is shown in Figure 2.

4. Terrestrial cosmic ray flux and atmospheric interactions

It is still unclear how much Earth's cloud cover is impacted by changes in solar activity. There is a widespread belief that the Sun has a major effect on Earth's atmospheric fluctuations because solar radiation intensity only slightly changes during a solar cycle [14]. Nonetheless, studies suggest that the Sun's modulation of the terrestrial cosmic ray flux (CRF) is a major solar effect that should be taken into account as a possible cause of climate change [15, 16]. Because the CRF produces ions that change the electrical conductivity of the atmosphere, it is regarded as a probable factor. This theory is supported by correlations between ice-rafted glacial debris and changes in ^{14}C and ^{10}Be accumulation rates. Such phenomena, observed in the North Atlantic, may contribute to global climate shifts. Observational findings further support the theory that the Sun-modulated CRF affects atmospheric electricity. This interaction, in effect,

sets off an amplification mechanism through which the Sun's role on Earth's ambient conditions gets magnified [17].

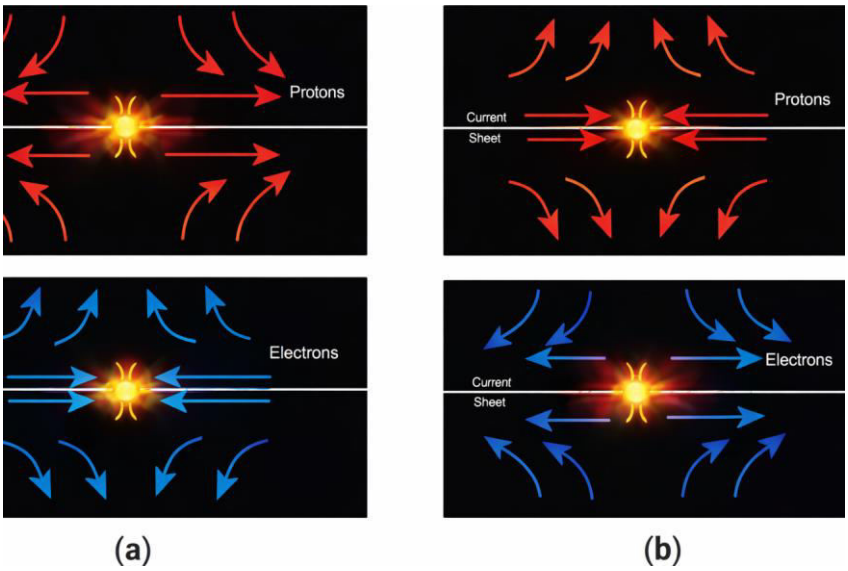


Fig.2. North-Seeking Solar Polarity (+ve) (b) South-Seeking Solar Polarity (-ve)

5. CRF-induced Modulation of Cloud Microphysics

Changes in high-energy particles, viz. cosmic rays, have received much attention from the scientific community, being considered either as a good indicator of solar irradiance or as a direct cause of climate change. Whatever the atmosphere is actually reacting to - the CRF, ultraviolet levels, or total solar irradiance - a significant "amplification" process must be invoked to explain the effects observed [18, 19]. Of these, the influence of CRF on cloud formation offers a more compelling explanation, even though a clear amplification mechanism for irradiance itself has not yet been identified. Dickinson, for instance, proposed that the extent of high-altitude cloud cover is altered by ion-mediated nucleation of sulfate aerosols [20], and similar ion-mediated nucleation has since been reported for sulfate and other aerosol species as well [21]. It is worthy to note, however, that this cosmic-ray-cloud hypothesis remains scientifically debated: controlled aerosol-chamber experiments at CERN's CLOUD facility have found that ion-induced nucleation, though measurable, is generally too small under present-day atmospheric conditions to produce the rise in cloud condensation nuclei needed to explain the variability actually observed in Earth's radiative budget [22]. Consequently, the magnitude of any CRF-driven climate effect remains an open and actively contested question rather than an established mechanism. It is nonetheless evident from analysis of the global electric circuit that the downward flow of vertical electric current density (Jz) is controlled by atmospheric temperature, pressure, and cloud dynamics, and that the solar-modulated CRF is a leading candidate for the main controller of this current. The concentration of cloud condensation nuclei (CCN) and the way ice forms in clouds are both affected by changes in the CRF, and precipitation patterns are, in turn, altered by these microscopic modifications [23]. The CRF thus offers a plausible physical connection between solar activity and Earth's environment by modifying the internal physics of clouds. Changes in Jz are statistically significantly correlated with meteorological responses, according to evidence from diurnal time scales, and cloud coverage over 11-year solar cycles is probably influenced by a similar process. However, a single model cannot easily explain these shifts, because cloud categories respond differently depending on their specific altitude and temperature; evaluating global mean effects therefore requires a more sophisticated, multi-layered modelling framework to account for these atmospheric variations.

6. Couplings Between Solar Activity and Terrestrial Climate

The Sun is a ball of gas and plasma (not a solid object like Earth); it does not rotate as one solid piece, with the equator rotating fastest (about 25 days for one full turn) and the poles rotating much more slowly. Figure 3 shows how different parts of the Sun's surface rotate at different speeds. At high latitudes and during glacial periods, a reduction in solar activity seems to be most effective. Ice-forming nuclei (IFN) were readily accessible during these periods owing to the atmosphere's high dust load [24].

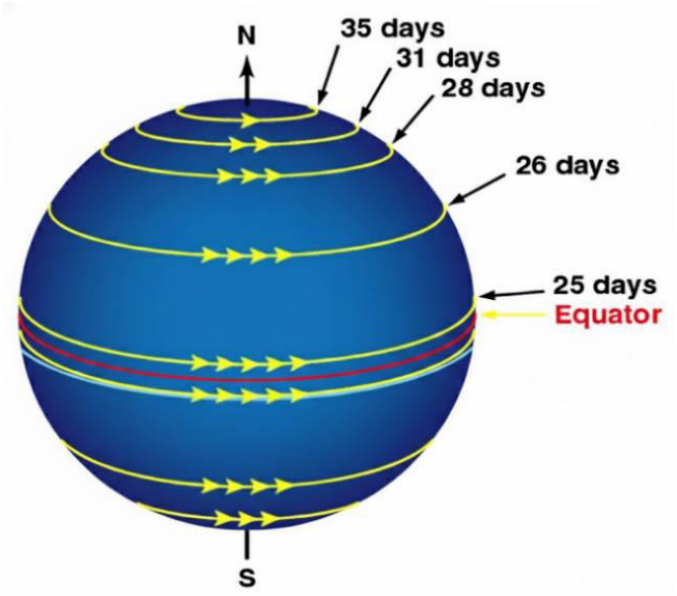


Fig.3. Surface differential rotation of the Sun (adapted from publicly available solar-cycle data [5])

Studies confirm that most nuclei in snow are composed of clays, which function as highly effective IFN, suggesting that the terrestrial cosmic ray flux (CRF) is an important mediator of the Sun-weather relationship [25, 26]. These findings, taken together, point towards the need for a more detailed investigation of how CRF variations influence the vertical current density (Jz) and the microphysical processes associated with it in the atmosphere. Incorporating such responses into suitable cloud-modelling frameworks will, in fact, be essential for a complete description of the global climate system.

This chain of influence is summarized in the block diagram of Figure 4: as solar activity rises, cosmic ray flux is suppressed, which in turn brings down the air-earth current, contact nucleation and precipitation, and correspondingly raises atmospheric dust loading.

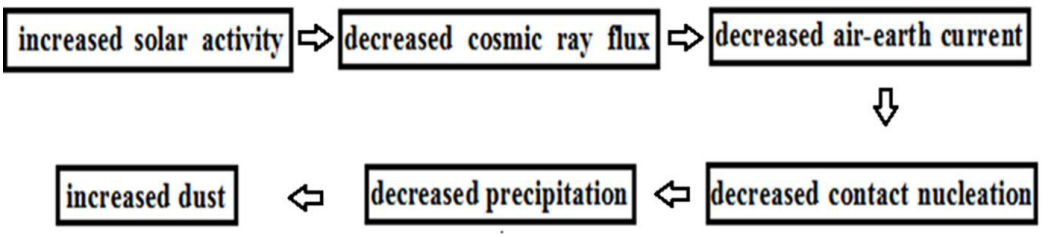


Fig.4. The connection between heightened solar activity and increased atmospheric dust

Long-term trends have been evaluated in Figure 5, which plots the variation of daily sunspot numbers (blue) and monthly sunspot numbers (red) over a 200-year period, viz. 1818 to 2020, reproduced from the NASA Marshall Space Flight Center solar-cycle archive for the purpose of illustrative comparison [27]. Figure 6, in addition, correlates the sunspot number with the open solar magnetic flux, reproduced from Solar and Heliospheric Observatory (SOHO) public data [28]. Cross-correlation of the sunspot series with neutron

monitor count rates indicates that cosmic ray intensity minima typically lag sunspot maxima by approximately 6 to 12 months, consistent with previously reported delay estimates of roughly 6 to 16 months that vary with solar-cycle phase and magnetic polarity [12, 16]. Figure 6 thus highlights the observed time difference between cosmic ray intensity and solar fluctuations, providing insight into the modulation delay within the heliosphere.

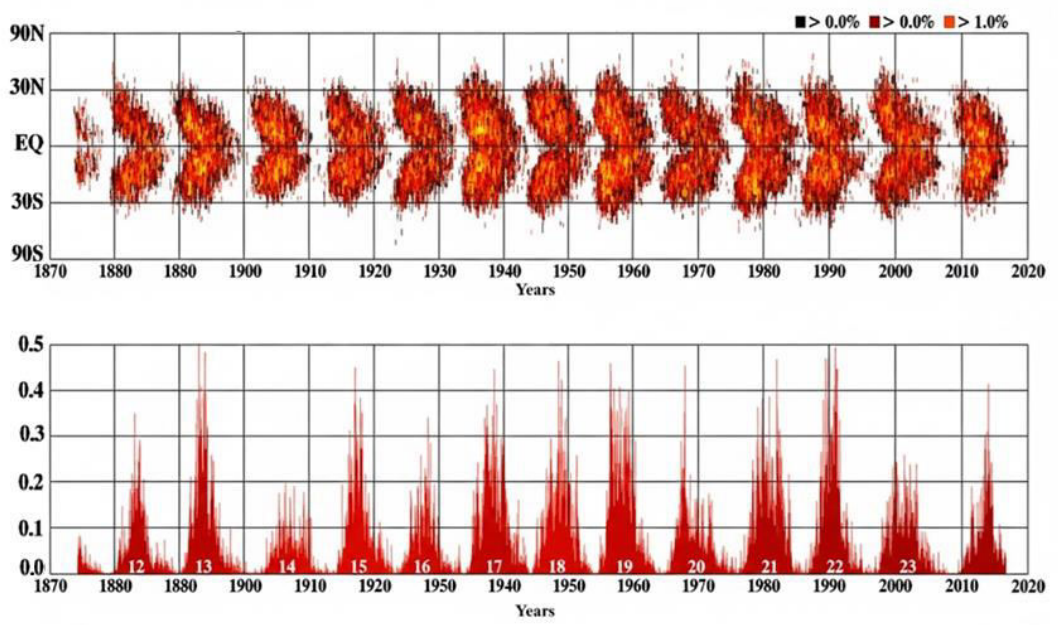


Fig.5. Periodic sunspot numbers for the last 150 years (data source: NASA Marshall Space Flight Center [27])

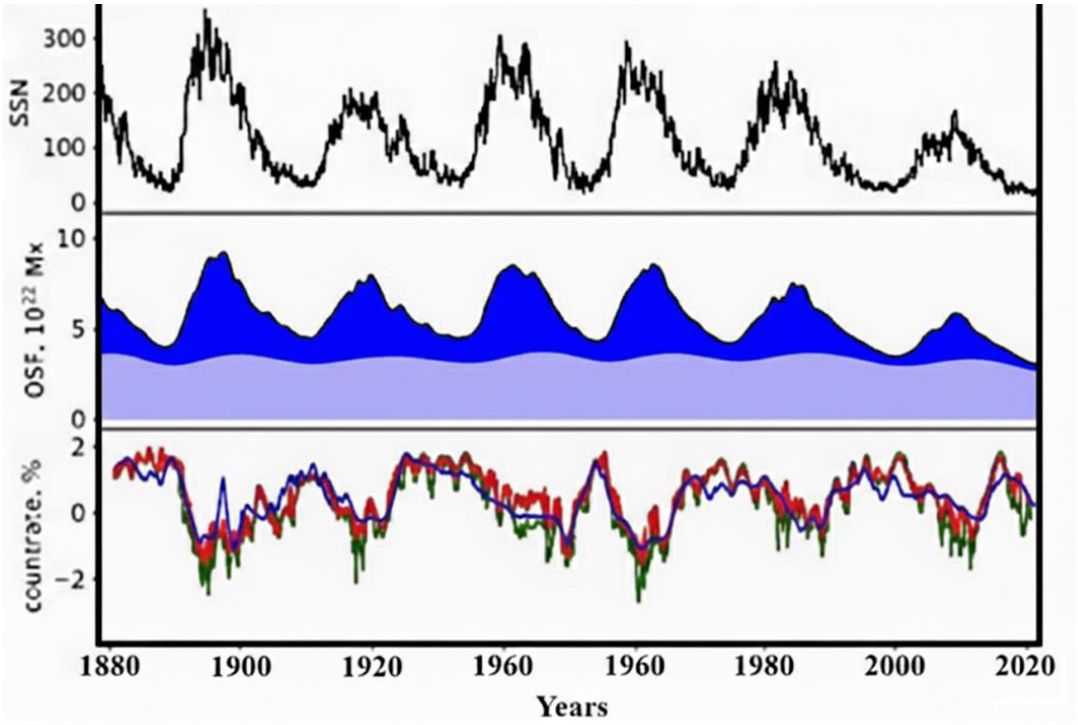


Fig.6. Sunspot number and open solar magnetic flux with time, and observed cosmic ray and solar variability (data source: Solar and Heliospheric Observatory [28])

7. Sunspot Number Variability on Long-Term Global Surface Temperature (GST)

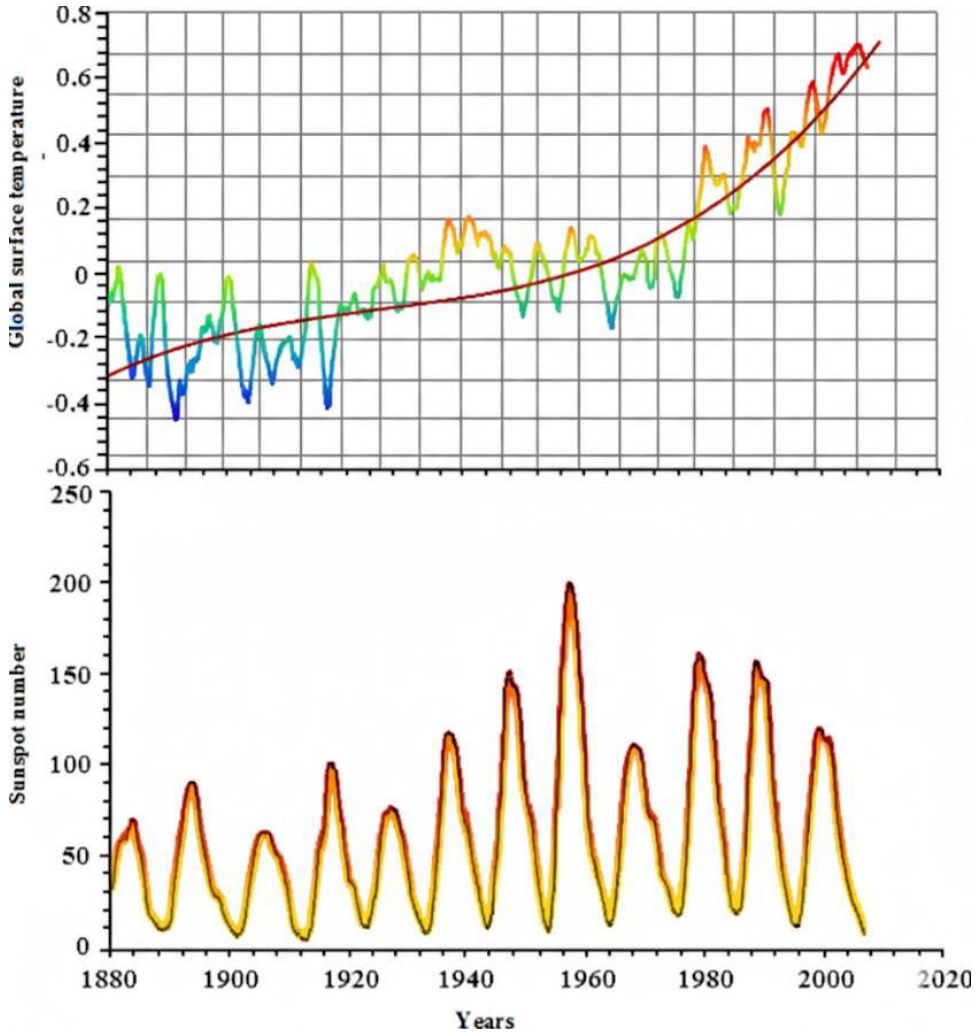


Fig.7. GST and the variation of sunspot numbers over the years (temperature data adapted from Berkeley Earth / IPCC AR6 [7, 8]; sunspot data from WDC-SILSO [5])

Global climate patterns and local weather are greatly influenced by the Sun. The climate is fundamentally shaped by any variation in the total solar energy that reaches the Earth. The incoming solar radiation and the long-wave radiation that the Earth emits are precisely balanced under stable atmospheric conditions, and this equilibrium determines the mean temperature of a given region. One important indicator of changes in climate is the measurement of the global surface temperature. Over the past 200 years, there has been a discernible warming of about 0.8 ± 0.18 ºC in the global surface air temperature (Figure 7), consistent with standard instrumental compilations such as the Berkeley Earth record and the IPCC Sixth Assessment Report [7, 8]. Published comparisons of decadally smoothed sunspot number and GST report a positive correlation, with Pearson coefficients on the order of r ≈ 0.5-0.7 for the pre-1980 record [29, 30]. This correlation weakens substantially after approximately 1980, when GST continues to rise while sunspot activity plateaus and then declines - a divergence widely interpreted as evidence that anthropogenic greenhouse-gas forcing has become the dominant driver of recent warming, even as solar variability continues to modulate climate on shorter time scales [7]. Although studies mainly link this warming to increasing greenhouse gas concentrations [25, 26], evidence points to solar variability as a contributing, secondary factor in global temperature fluctuations [3-4, 9-13]. The 11-year cycle, and its bearing on Earth's electromagnetic environment, has remained a focus of scientific investigation over recent decades [29, 30]. This periodic variability, in a broader sense, provides a framework for understanding how solar fluctuations

contribute to global warming through their effect on the energy balance, though without displacing greenhouse-gas forcing as the primary driver of the long-term warming trend.

8. Conclusion

This review has traced the physical chain linking solar activity to Earth's climate: modulation of galactic cosmic ray flux by the heliospheric magnetic field, the resulting changes in atmospheric ionization and electrical conductivity, and their proposed - but not fully confirmed - influence on cloud condensation nuclei and cloud cover. The evidence for a cosmic-ray-cloud amplification mechanism remains mixed: correlations between CRF, ice-rafted debris, and cosmogenic isotopes support a role for solar-modulated cosmic rays, yet CLOUD-facility experiments indicate that the resulting aerosol nucleation is generally too weak on its own to account for the full observed variability in Earth's radiative budget. Set against this, the sunspot-GST correlation reported here ($r \approx 0.5$-0.7 before 1980) weakens sharply in the post-1980 record, during which greenhouse-gas forcing has become the dominant driver of global warming; solar-cosmic ray coupling should therefore be understood as a secondary modulator of climate variability rather than a substitute for anthropogenic forcing.

The principal contribution of this work is the consolidation of solar, cosmic ray, and climate datasets into a single comparative framework, together with quantitative estimates - a 6-12 month solar-cosmic ray lag and the pre-/post-1980 correlation contrast - that are not readily available together in a single source in the existing review literature. Its main limitation is that it relies on secondary, published data and correlation-level comparisons rather than an independent statistical re-analysis of the raw time series; a natural next step is a dedicated cross-correlation and regression analysis of the WDC-SILSO, NMDB, and GST records at their original sampling resolution, together with a systematic comparison against CLOUD-experiment nucleation rates. Taken together, the evidence reviewed here suggests that stratospheric solar forcing plays a meaningful, if secondary, role in shaping tropospheric climate mechanisms. Such top-down and bottom-up couplings provide a plausible, though not yet fully quantified, pathway through which comparatively small solar variations could contribute to terrestrial weather patterns, alongside - not instead of - the dominant influence of greenhouse-gas forcing on long-term climate trends.

Acknowledgement

The authors gratefully acknowledge the public data repositories - including WDC-SILSO, NMDB, Berkeley Earth, and NASA/GISS - whose solar activity and climate datasets underpin this study.

Nomenclature and abbreviations

GCR – Galactic Cosmic Ray

CRF – (Terrestrial) Cosmic Ray Flux

GST – Global Surface Temperature

IFN – Ice-Forming Nuclei

CCN – Cloud Condensation Nuclei

Jz – Vertical (air-earth) electric current density

UV – Ultraviolet radiation

OSF – Open Solar (magnetic) Flux

SSN – Sunspot Number

nT, G – nanotesla, Gauss (units of magnetic field strength)

MeV – Mega electron-volt (unit of particle kinetic energy)

WDC-SILSO – World Data Center for the Sunspot Index and Long-term Solar Observations

NMDB – Neutron Monitor Database

SOHO – Solar and Heliospheric Observatory

IPCC AR6 – Intergovernmental Panel on Climate Change, Sixth Assessment Report

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4

Optimization and Cost Analysis of Electrocoagulation for Phenolic Syntan Removal from Synthetic Tannery Wastewater

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Abstract

Syntans are phenol-based synthetically produced tanning agents used in tanneries for improving the filling, grain properties and dyeing property of the hide. A significant portion of syntans emanating in the tannery effluents along with other heterocyclic aromatic compounds have high pollution load and imposes severe environmental impact. Hence, the present study adopted an Electrocoagulation (EC) method with perforated aluminum electrodes for the removal of phenolic syntan (PS) from PS bearing synthetic tannery wastewater. The one-variable-at-a-time (OVAT) experimental analysis was performed to optimize the PS removal efficiency. The OVAT experiments were studied to understand the impact of operating parameters, i.e. initial pH (3 - 7), current density (5.8 - 23.6 mA/cm²), and initial phenolic syntan (PS) concentration (0.25 - 1.5 g/L). The mixing speed was maintained at 200 rpm in each experiment. The results demonstrated that the EC process could efficiently remove PS (83.43%) from synthetic wastewater at the following operating condition: initial pH= 4, current density= 17.64 mA/cm² and initial PS concentration= 0.25 g/L, and electrolysis time = 90 minutes. The cost analysis showed the economic feasibility of EC techniques with a total cost of $3.46/m³ and demonstrated the need for a balance between the EC unit effectiveness and operating costs for economically viable wastewater treatment in the tannery sector. The study provided valuable information for improved sustainable and economical effluents treatment techniques in tanneries.

Keywords

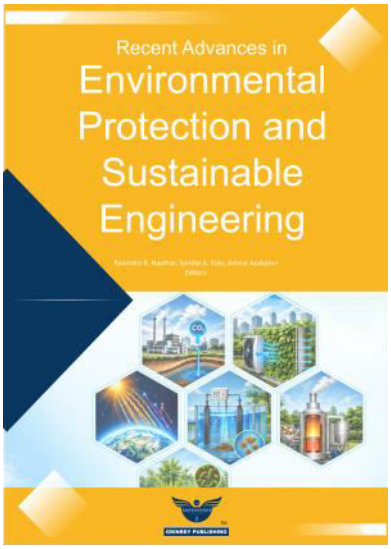
Carbonation Electrocoagulation, Syntan, One-Variable-at-a-Time (OVAT) Optimization, Operational cost.

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1. Introduction

The tanning process has been identified as among of the most water-polluting manufacturing processes producing huge quantities of wastewater with a highly intricate composition due to the presence of organic and inorganic contaminants. Among the organic contaminants, synthetic tanning agents (syntans), which are a type of phenol-based substance have been commonly utilized to enhance filling, grain, and color properties of leather. However, owing to their complex aromatic structure, they are recalcitrant in nature and highly toxic, leading to considerable environmental implications [1, 2]. These phenolic derivatives, obtained from phenols, cresols, naphthalene, melamine, and acrylic derivatives by formaldehyde-sulfuric acid treatment reactions, tend to remain unabsorbed by hide/skin in most tanning operations and are deposited into tannery wastewater streams [3, 4]. Due to their persistence, and resistance to biodegradation, these compounds render traditional biological treatment plants ineffective [3, 5]. Therefore, untreated or partially treated syntan-containing tannery wastewaters can have drastic effects on aquatic environments due to their bioaccumulation and toxicity to biotic species.

Various physico-chemical and advanced oxidation processes i.e., Fenton oxidation, ozonation, UV irradiation, and photo-catalysis have been explored for syntan degradation [6, 7]. Although such strategies can be efficient in degrading phenolic compounds, their use in real-scale tannery effluent treatment plants is limited due to the high operating costs, energy demands, and need for intricate operation control [1]. Alternatively, adsorption and coagulation processes, although cost-effective, are usually linked with very high hazardous sludge generation and restrictions in its disposal. Therefore, there is an urgent need for alternative treatments options that strike a balance between efficiency, sustainability, and economic viability.

Electrocoagulation (EC) has proven to be a viable solution for treating industrial effluents from various source, such as tannery, textile, food processing, and electroplating industries [8, 9]. The process involves in-situ generation of coagulants via electrochemical disintegration of the sacrificial anode (usually aluminum or iron), which destabilize contaminants, resulting in their aggregation and removal. the major benefits of this process are minimal chemical usage, easy operation, lower sludge yield, and suitability for on-site treatment [10, 11]. In recent research, EC was seen to attain significant elimination of chemical oxygen demand, total organic carbon and phenolic syntans at engineered conditions [7, 12]. However, limited systematic studies have been performed by optimizing the operational parameters like initial pH, current density, and initial syntan concentration in the influent for enhanced syntan removals, for reducing the overall cost of operation and electrical energy requirements.

The current research adds to the prevalent body of work by systematically examining a lab-scale EC process using stationary perforated Al electrodes for removal of phenolic syntans from simulated tannery wastewater. In contrast to the previous studies that mainly considered pollutant removal efficiencies, the current work prioritizes a holistic assessment by coupling treatment performance with operating cost and energy consumption. Optimization was performed using the one-variable-at-a-time (OVAT) method to investigate the significant role of input operating variables like pH, current density, and initial syntan concentration on the performance of the lab-scale EC treatment unit.

The main objective of the present investigation is to maximize the electrocoagulation (EC) process for efficient elimination of phenolic syntans from model tannery wastewater with a view to ensuring cost-effectiveness. In the above context, the study aimed at assessing the impact of the most important operating factors (viz., initial pH, current density, and pollutant concentration) on the efficacy of syntan removal. Special focus was given to the detection of the best operating conditions which ensured a proper balance between high removal efficiency, smaller electrolysis time, lower specific energy consumption (SEC), and

lowest operational costs. Additionally, the cost–benefit analysis was carried out for the EC process in order to determine its economic viability, so as to position the treatment process as sustainable and scalable for tannery wastewater treatment. The general direction of this investigation is toward building deeper understanding of EC process for efficient treatment of phenolic compound-contaminated effluents, and ultimately achieving environmentally friendly and industry-specific wastewater treatment approach.

2. Materials and Methods

2.1. Chemicals

In this investigation, commercial Phenolic Syntan (Basyntan DI) was acquired from M/s BASF India Ltd., Kanpur, India. Various other chemicals were utilized in this study i.e. hydrochloric acid (35 – 37%, Molychem, Thane, India), sodium hydroxide (AG,98%, SRL, Maharashtra, India), sodium chloride (AG, 99%, Merk Life Science Pvt. Ltd., Mumbai, India).

2.2. Electrocoagulation setup

The lab-scale batch EC unit was constructed of plexi-glass and had a working capacity of 1000 mL. EC reduction was carried out using Al anode-cathode electrodes. The Al electrodes were of dimensions 8.5 cm × 5 cm × 0.2 cm, with an effective surface area of 85.63 cm^2. Each electrode had a total of 10 perforations, with each opening having a diameter of 0.2 cm. Perforated aluminum electrodes were used to enhance electrolyte circulation and mass transfer within the EC reactor. The perforations can help release gas bubbles, decrease the concentration polarization, and enhance efficient utilization of the electrode surface, leading to better EC performance than the traditional solid plate electrodes [11, 13]. The two aluminium electrodes had a fixed spacing of about 2 cm., A magnetic stirrer was employed to maintain a normalized solution throughout the treatment process at a constant rate of 200 RPM. Anode-cathode were linked to a direct current (DC) power source (0 - 5 A, 0 - 30 V; Testronix) in a monopolar arrangement (Figure 1). The typical EC reactions expected in the reactor are given below in Table 1 [13].

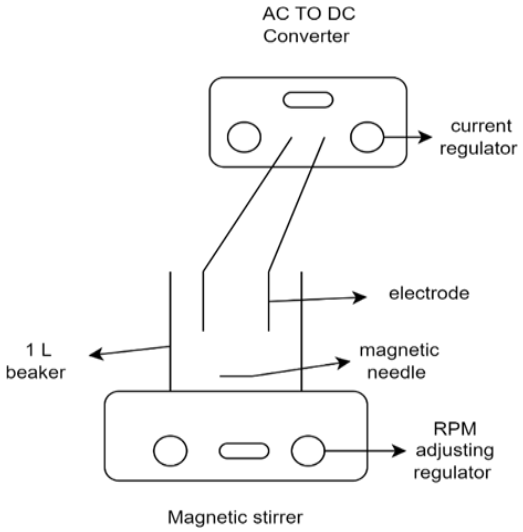


Fig. 1. EC Experimental Setup

Table 1. Anode and Cathode Reactions in EC Process.

At Anode	$Al\ (s) \rightarrow Al^{3+}\ (aq) + 3e^-$ $2H_2O\ (l) \rightarrow O_2\ (g) + 4H^+(aq) + 4e^-$
At Cathode	$2H^+\ (aq) + 2e^- \rightarrow H_2(g)$ $2H_2O\ (l) + 2e^- \rightarrow H_2(g) + 2OH^-\ (aq)$
Overall reaction	$Al^{3+}\ (aq) + 3OH^-\ (aq) \rightarrow Al(OH)_3\ (s)$

2.3. Experimental Procedure

To prevent variations in wastewater properties, simulated tannery solution was freshly created at the beginning of each experimental run. The desired syntan concentrations (i.e., 0.25 - 1.5 g/L) were maintained in the simulated tannery solution by adding required quantities of syntan powder to tap water. The characteristics of the prepared simulated wastewater are shown in Table 2.

Table 2. Characteristics of Synthetic Wastewater

Concentration of Phenolic Syntan (g/L)	pH	UV_{280} Absorbance	Conductivity (µS/cm)
0.25	7±0.3	1.32	760 ± 50
0.50	7±0.3	2.65	760 ± 50
1.0	7±0.3	5.3	760 ± 50
1.50	7±0.3	7.95	760 ± 50

0.1M HCl or 0.1M NaOH were added in solution to maintain the initial pH (3-7). The conductivity was maintained at 1.50 mS/cm during electrolysis by adding 1.5 g/L of NaCl to the synthetic wastewater. During each experimental run, samples were collected from the EC batch reactor for data analysis at an interval of 10 minutes upto 90 minutes. Later, the treated effluent samples were filtered by Whatman filter paper (0.45-micron pore size) and analyzed immediately to avoid estimation errors. Samples of raw and treated syntan were analyzed for UV280 to determine the degree of degradation of syntan. At the start of an experimental run, the electrodes were rinsed with diluted HCl and wiped with distilled water, to eliminate passivation from the electrode surface. The process optimization was performed in a systematic OVAT mode, where one parameter was varied within a specific range and the remaining three input operating variables were kept constant. The parameters were sequentially optimized based on successive measurements in experiments to get the optimal working conditions for maximum PS removal (Table 3).

Table 3. Experimental analysis Layout

Operating parameters their value	Experimental Phases		
	Phase -I	Phase -II	Phase -III
Initial pH = 3-7	Variable	Fixed (optimal)	Fixed (optimal)
Current intensity (mA/cm^2) = 5.8 – 23.3	Fixed	Variable	Fixed (optimal)
Initial PS concentration (g/L) = 0.25 – 1.5	Fixed	Fixed	Variable

In this study, the OVAT method was chosen due to its simplicity and systematic approach to assess the distinct impact of each operational variable on the EC efficiency while fixing the other variables constant. Therefore, the OVAT was considered suitable since the main objective of this study was to determine the individual effect of initial pH, current density and phenolic syntan concentration and determine suitable operational conditions for a laboratory-scale EC system. But this approach has inherent constraints. In contrast to statistical optimization methods like Response Surface Methodology (RSM), OVAT has the disadvantage of not being able to assess interactions between variables, may require a higher number of experiments to find the optimal conditions [14]. Hence, while OVAT is useful for early process optimization and mechanistic comprehension, future investigations should use multivariate optimization methods like RSM for investigating variable interactions as well as improving process efficiency.

2.4. Operational Cost Estimation

The purpose of treatment cost analysis for EC unit was to understand the economic benefit of the process without having to compromise on the system performance. The unit energy consumption and electrode dissolution were determined for the EC process. Electrode dissolution and energy consumption were determined for the optimum working condition obtained for the treatment approach. The operating cost was calculated by the equation as follows [13]:

$$Operating\ Cost\ \left(\frac{\$}{m^3}\right) = (a \times EMC) + (b \times ELC) \quad (1)$$

Where,

'a' refers to the unit costs of electrode material (0.73 USD kg^{-1}) and 'b' refers to unit cost of electric energy (0.078 USD kWh^{-1}). EMC refers to electrode material consumption (kg m^{-3}) and ELC refers to energy consumption (kWh m^{-3}).

2.4.1. Electrode material consumption

In EC process, the mass of electrode dissolution was determined using Faraday law [10].

$$EMC = \frac{(M \times I \times t)}{(Z \times F \times V)} \quad (2)$$

Where, M: Molecular weight material used in EC process i.e. Al, I: Current intensity (amp), t: Time (sec), z: valency of metal ion (e^-/mol), F: Faraday constant, (96500 coulomb/mol), V: volume of solution (m^3).

In conventional chemical precipitation procedures, the coagulant dose is determined from the quantity of disintegrated anode material. In another way, the amount of coagulant needed for traditional chemical precipitation processes is directly proportional to the quantity of material which emerges from the anode in EC. Therefore, the cost related to the consumption of the anode is identical for EC procedure and for conventional chemical coagulation methods. The comparison of chemical coagulation and the EC process does not take into account this cost element.

2.4.2. Energy consumption

Energy consumption for treatment unit at optimum condition is calculated using following formula [10].

$$SEC = \frac{V \times I \times T}{Q \times 1000} \quad (3)$$

Where, SEC: Specific energy consumption (kWh/m^3) V: Voltage, I: Current (A), T: Operating time (hr), Q: Volume of treated wastewater (m^3)

3. Results and Discussion

3.1. Impacts of influent pH

The influent pH of simulated solution is a critical parameter that can directly influence the efficacy of the EC process. This input variable primarily governs the solubility and precipitation of metal hydroxides in the

EC process [15]. pH also determines the elimination mechanism of contaminants in the EC reactor [15]. The impact of various initial pH (3-7) on the PS elimination in synthetic solution was investigated in EC method. Whereas, other operating conditions i.e. CD and initial PS concentration to be 11.6 mA/cm^2 and 0.5 g/L, respectively (shown in figure 2).

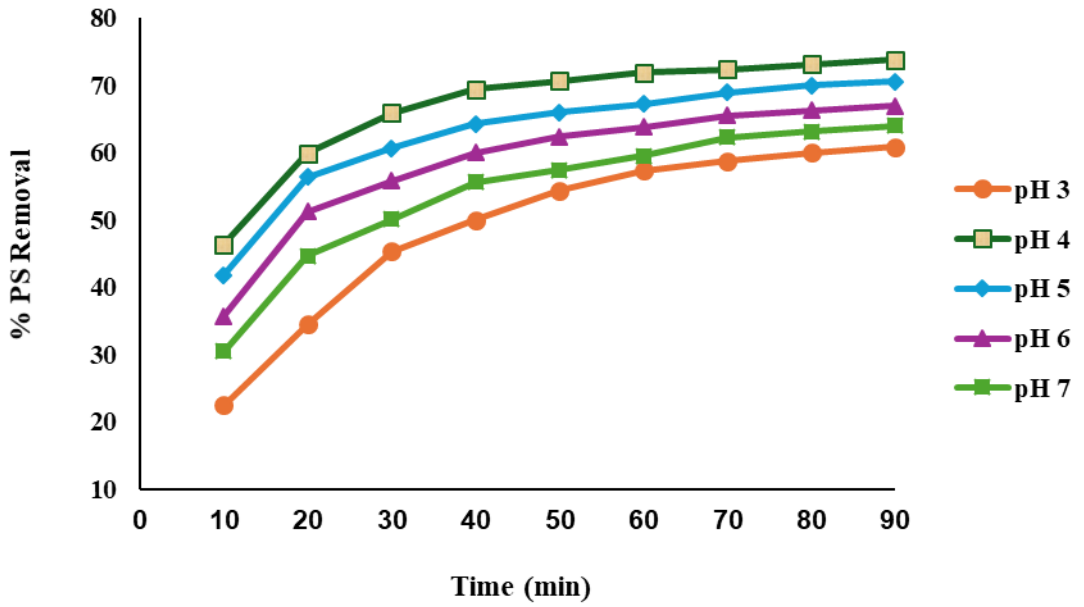


Fig. 2. Impacts of varying influent pH on the PS removal in EC process

After 90 minutes of electrolysis time (ET), 60.88% of the PS was removed at influent pH 3. As the influent pH increased from 3 to 4, PS elimination increased by 13% after 90 minutes of ET. At 90 minutes of ET, PS elimination reduces by 7.2% to 3.6% and 3% when the influent pH increases from 4 to 5, 5 to 6, and 6 to 5, respectively. The highest PS removal (73.8%) was obtained at an influent pH of 4, which is considered the optimal pH for PS removal. Therefore, influent pH 4 was maintained constant in subsequent trials when other parameters were one at a time changed. Fig. 2 indicates that PS removal was found to be more efficient under weakly acidic conditions, while strongly acidic and alkaline conditions were found to be less efficient. During experimental analysis, pH of treated solution was also observed to change in alkaline direction during treatment and ranges from 5 to 7 at influent pH of 4. This was due to the production of OH^- ions in EC process as a result of electrolysis of wastewater (as clear from Table 1), which further increased the pH of treated solution. Kim et.al, explains this behavior expected and asserts $Al(OH)_4^-$ to be the Al species in very alkaline conditions, which have poor coagulation properties [16]. Anode-formed Al cations can produce polymeric species like $Al_{13}O_4(OH)_{24}^{7+}$ and precipitated $Al(OH)_3$, and thereby make coagulation more effective when carried out under a weakly acidic condition (pH 6-7) [17]. These $Al(OH)_3$ species can adsorb the PS compounds and eliminate them from solution [18].

3.2. Impact of Current Density

Current density (CD) is a critical factor in regulating the rate of EC reactions [19]. This parameter plays an important role in electrode disintegration, power consumption, pH of treated sample and the yield of $Al(OH)_3$ flocs [20]. Thus, this parameter may have substantial effects on pollutant removal efficiencies. Figure 3 shows the impact of CD on PS elimination efficiency. Here, sets of experiments were conducted at various CD (5.8 – 23.3 mA/cm^2). Remaining factors i.e. influent pH and initial PS concentration were kept constant as 4 and 0.50 g/L respectively.

Figure 3 (a) indicates the PS removal 69% was found at minimum CD of 5.8 mA/cm^2 after 90 minutes of ET. An improvement in CD from 5.8 to 11.6 mA/cm^2 and from 11.6 to 17.6 mA/cm^2 resulted in a rise in the

PS elimination from 69% to 73.8% and 73.8% to 83.43%, respectively after 90 minutes ET. However, the main consequences of increasing CD were the elevated rate of anode dissolution. This should raise the amount of $Al(OH)_3$ flocs in the solution, and subsequently improve the rates of pollutants removal [21]. Table 4 displays that a rise in CD from 5.8 to 11.6 mA/cm^2 and from 11.6 to 17.6 mA/cm^2 enhanced higher anode dissolution (from 0.252 to 0.503 kg Al/m^3 and from 0.503 to 0.755 kg Al/m^3) after 90 min ET.

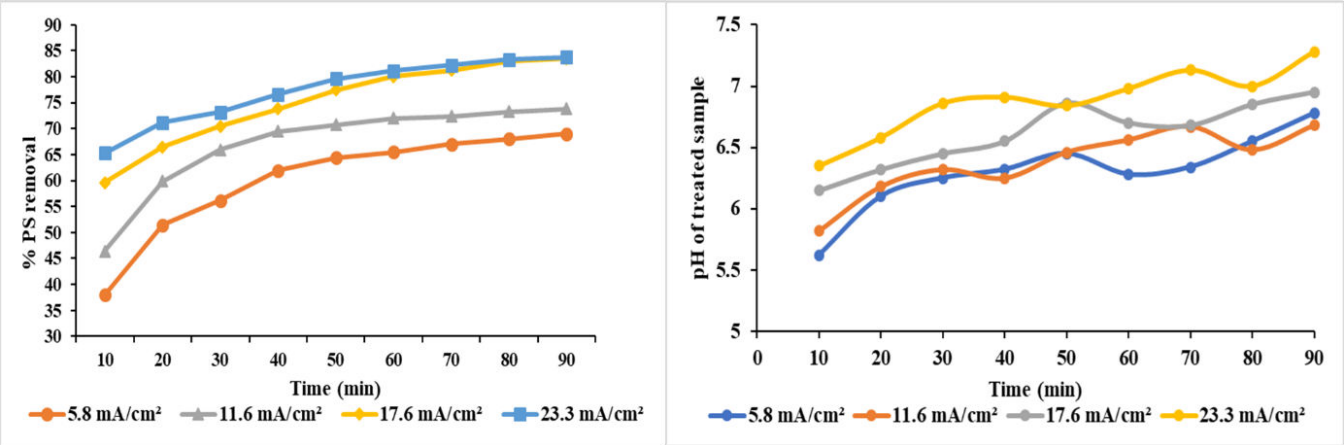


Fig. 3. (a) Impacts of varying CD on the PS removal in EC process. (b) Variation of treated solution pH with electrolysis time at various CD

Figure 3(b) shows the shift of pH of treated solution with electrolysis time at various CD. pH progressively increased over the entire EC procedure regardless of CD. It raised from 5.62 to 6.78, 5.82 to 6.68, 6.15 to 6.95 and 6.35 to 7.28 at 5.8, 11.6, 17.6 and 23.3 mA cm^{-2}, respectively. The rise in pH is primarily due to the production of hydroxide ions (OH^-) at the cathode throughout the reduction of water, which favors the production of amorphous $Al(OH)_3$ flocs that facilitate the elimination of pollutants [21]. At higher current densities, relatively higher value of final pH was found due to greater rate of electrochemical reactions and formation (OH^-). However, the treated solution still remained in the near-neutral pH range (~6.7–7.3), which is suitable for the generation of $Al(OH)_3$ species and efficient EC performance [22].

Table 4. Energy consumption, electrode dissolution and operating cost for various CD in EC process

Time	CD = 5.8 mA/cm^2			CD = 11.6 mA/cm^2			CD = 17.6 mA/cm^2			CD = 23.6 mA/cm^2		
(min)	SEC	EMC	Cost	SEC	EMC	Cost	SEC	EMC	Cost	SEC	EMC	Cost
10	0.27	0.028	0.10	0.917	0.056	0.24	2.03	0.084	0.41	3.53	0.112	0.62
20	0.50	0.056	0.20	1.767	0.112	0.46	4.00	0.168	0.81	7.00	0.224	1.22
30	0.70	0.084	0.29	2.550	0.168	0.69	5.85	0.252	1.21	10.30	0.336	1.82
40	0.90	0.112	0.39	3.333	0.224	0.91	7.60	0.336	1.59	13.47	0.447	2.40
50	1.04	0.140	0.48	4.000	0.280	1.13	9.38	0.419	1.98	16.50	0.559	2.98
60	1.20	0.168	0.57	4.700	0.336	1.34	10.95	0.503	2.35	19.60	0.671	3.56
70	1.34	0.196	0.66	5.250	0.391	1.55	12.60	0.587	2.72	22.63	0.783	4.13
80	1.40	0.224	0.747	6.000	0.447	1.77	14.20	0.671	3.09	25.33	0.895	4.67
90	1.50	0.252	0.83	6.600	0.503	1.97	15.75	0.755	3.46	28.20	1.007	5.23

Where, SEC in kWh/m^3; EMC in Kg Al/m^3; Cost in $/m^3.

According to Faraday's law (Equation 2), electrolysis time (ET) and CD are directly proportional to the amount of Al^{3+} ions produced during EC practice. Hence, the production of $Al(OH)_3$ flocs rises with rising CD for higher pollutant removal. Further, higher current densities have been reported to improve generation of tinny bubbles at the cathode, hence leading to better flocculated contaminant flotation in the EC unit [22]. As shown in Figure 3, an increase of CD from 17.6 to 23.3 mA/cm² resulted in merely a negligible rise in PS removal (0.28%), whereas SEC and OC rose by 44.15% and 33.84%, respectively (Table 4). This is because the efficiency of removal was not proportional to the increase in current density due to the fact that a greater portion of the current might be used for the oxygen evolution reaction (OER), which is competing with the anodic dissolution of aluminum. Therefore, the current efficiency for the production of Al^{3+} ions becomes lower and the energy consumption becomes greater. This phenomenon has been well known in the case of EC processes using Al electrodes, due to the increased rate of oxygen evolution with higher anodic potential (Mollah et al., 2004; Chen, 2004; Hakizimana et al., 2017). The best CD was thus determined to be 17.6 mA/cm² from these observations.

3.3. Impact of Initial PS Concentration

In the instance of industrial effluents the aqueous concentration of the pollutant emitted from various manufacturing processes varies widely. Therefore, the impact of different initial PS amounts on the efficacy of the EC procedures should be explored. The effect of different initial phenolic syntan concentration (0.25-1.5 g/L) in the EC procedures was studied while the remaining parameters were maintained as CD 11.6 mA/cm2 and pH 4. The results (Figure 4) demonstrate a noticeable reduction in PS removal efficacy with rise in initial PS concentration.

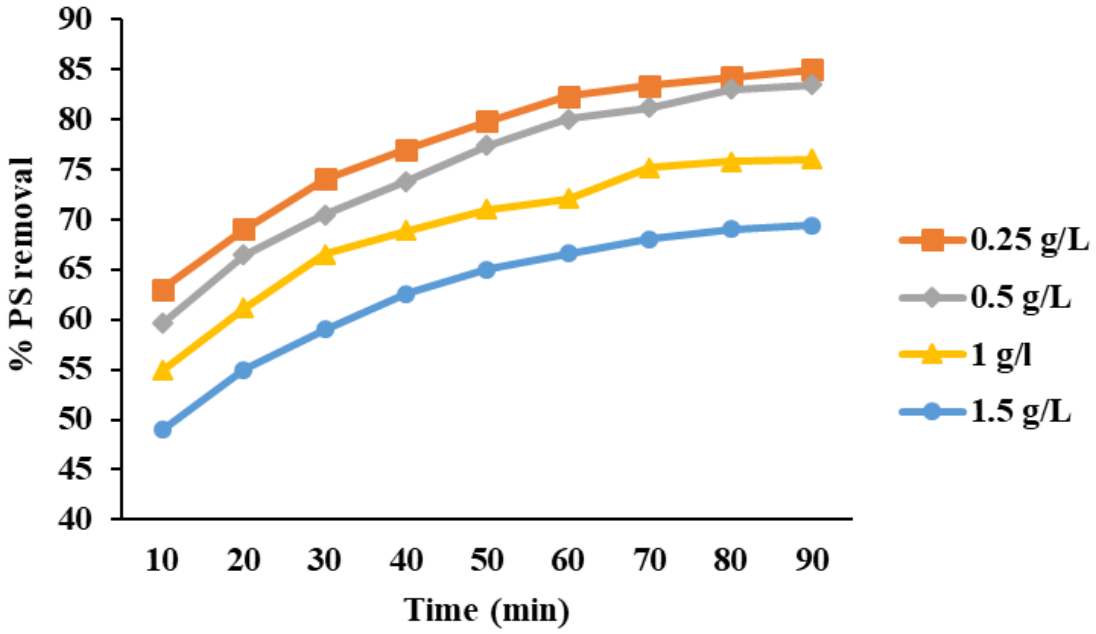


Fig. 4. Impacts of influent PS concentration on the PS elimination by EC process

The PS removal efficiencies were 85 %, 83.43 %, 76.03 % and 69.4 % at various PS concentrations of 0.25 g/L, 0.50 g/L, 1.0 g/L and 1.5 g/L respectively, after 90 minutes ET. Lower PS removal with higher influent PS concentrations may have been caused due to congestion of PS compounds onto the surface of $Al(OH)_3$ flocs. The PS concentration was substantially higher than the overall floc quanity. The influent PS concentrations doesn't have any impact on the amount of anode dissolution based on Faraday's law. For the fixed CD and ET, the rate of generation of $Al(OH)_3$ flocs produced would be very close to being constant [11, 17].

3.4. Comparison of various treatment approaches for syntan elimination

Table 5. Comparison of various treatment techniques for syntan removal.

Treatment method	Operating conditions	Removal efficiency	Main limitations	Reference
Ozonation	pH = 7, O_3 dose = 1/h	COD = 91%, tannin = 98%, UV absorbance = 99%	High ozone demand and energy consumption; partial mineralization	[26]
Ozonation	Initial syntan = 500 mg/L, pH = 7	COD removal = 84.2% UV_{280} = 92%	Requires ozone generation and specialized equipment	[27]
Biological degradation (*Trametes versicolor*)	Initial syntan = 500 mg/L; Treatment time = 8 days	COD = 76.66%, TOC 72.94%; higher with co-substrate	Long treatment time	[28]
Biological degradation (*Trichoderma aureoviridae*)	Syntan = 400 mg/L; incubation = 8 days	COD = 82.3%, TOC = 51.6%; BOD = 41.6%	Slow kinetics; suitable mainly as biological polishing	[29]
EC process (Present study)	Al electrodes, CD = **17.6 mA cm^{-2}**, pH = 5, ET = 90 min	**Syntan removal = 83.43%**,	Electrode consumption and sludge generation	Present study

Table 4 illustrates the comparison between the efficacy of the EC process carried out in the current research and the performance of other processes that have been used in the treatment of phenolic syntan. The use of ozonation in the treatment of phenolic syntans has been shown to result in up to 98% removal of tannins and 91% removal of COD, as well as improvement of wastewater biodegradability; however, the process is associated with continuous ozone production and high energy consumption. The use of Trametes versicolor and Trichoderma aureoviridae in biological wastewater treatment processes is environmentally friendly, but it takes days to degrade phenolic syntans because they are very difficult to degrade. On the contrary, the EC process conducted in the present study resulted in 83.43% removal of phenolic syntan within 90 min using optimal operation conditions, without any addition of external oxidants.

4. Conclusion

In this study, the batch scale electrocoagulation (EC) process with aluminum anode was successfully used for removal of phenolic syntan (PS) from simulated tannery wastewater. OVAT analysis revealed an optimum pH of 4, which not only increased PS removal efficiency but also decreased electrolysis time drastically, consequently reducing specific energy consumption (SEC) and cost of treatment. Current density was also important, and 17.6 mA/cm² was the optimum operating point, providing a 14.43% higher PS removal than that at 5.8 mA/cm² without incurring the steep SEC (44.15%) and cost (33.84%) rise experienced at a higher current density (23.3 mA/cm²). More importantly, the highest PS removal occurred at the lowest initial PS concentration (0.25 g/L). The best elimination efficiency (83.43%) was found at optimal conditions of CD 17.6 mA/cm², initial pH 4, and PS concentration 0.25 g/L, with the corresponding SEC of 15.75 kWh·m^{-3} and operational cost of 3.46 \$·m^{-3}.

In general, the results showed that EC treatment using aluminum electrodes is a highly efficient and economically feasible treatment method for phenolic syntan-bearing tannery wastewater. This process has

great potential for industrial applications for achieving high pollutant removals coupled with low energy requirements and operational costs, and thereby contributing to sustainable tannery wastewater treatment.

The results obtained from this research study are very important regarding the EC of phenolic syntan in the laboratory setup. However, tannery effluent is a complex system that contains high concentrations of organic and inorganic contaminants which can affect the efficiency of the electrocoagulation process. Therefore, wastewater containing higher concentration of contaminants requires more electrolysis time, higher current density, or multiple stages in order to obtain similar removal efficiencies. Despite being very important in designing the process, the optimum operating parameters found in this study must be investigated further using actual tannery effluent.

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5

Development and Experimental Assessment of an Induction-Heated Sanitary Waste Incineration System

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Abstract

The recent developments in energy and environmental engineering show the significance of decentralized and energy-efficient systems to the safe handling of sanitary waste. Inappropriate disposal of the used sanitary napkins causes contamination of the environment, toxic gases, and health hazards to the people. The paper is a design, fabrication, and experimental analysis of a portable sanitary napkin incinerator that was designed under the purview of energy-efficient systems. The proposed incinerator of 61 cm x 10 cm x 8 cm size, uses electric-heating technology. The system works under a 2000 W nichrome heating coil operating at 230 V with a sanitary napkin capacity of 5-10 in a cycle. Trials conducted in the laboratory showed full combustion in 170 to 200 s per batch. The evaluation of performance revealed that there was a mean waste mass decrease of about 91 % with the residual inert ash mass of between 3.4 g to 5.1 g per cycle which proves that the performance of volume reduction was achieved. Operating temperatures of 800-1050°C were maintained during combustion. The filtration unit containing activated carbon and gravel was intended to reduce different pollutants. Approximate fabrication cost of the prototype was INR 8,000-12,000, while the operating electricity cost was about INR 2–4 per cycle depending on operating time and local electricity tariff. The results show that energy- efficient systems can be successfully incorporated in small scale incineration system to provide a sustainable resolution to the use of decentralized sanitary waste in the field of environmental engineering.

Keywords

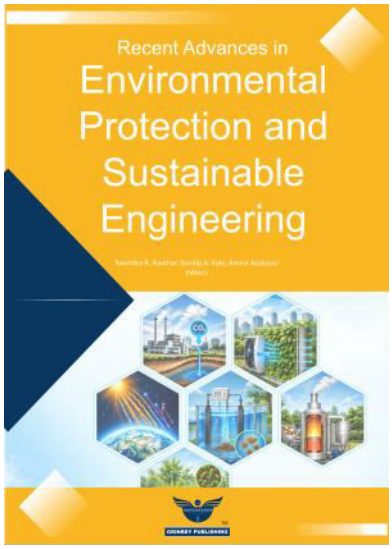
Carbonation Incinerator; Nichrome heating; Energy; Environmental; Combustion

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1. Introduction

The control of menstrual hygiene has become the international concern, especially in low-income regions where it is still a significant obstacle to the health and career development of women [1]. The practical evidence in India has shown that unhygienic menstrual habits tend to initiate the occurrence of urogenital infection, therefore need to underline the fact that clean practices and good sanitation systems are not only luxuries but necessities [2].

The growing preference for disposable wipes reflects a significant cultural evolution in menstrual management. Nevertheless, as these products become the standard in low-income areas, the resulting sanitary debris creates a pressing environmental challenge that demands immediate mitigation [3]. This trend is further accelerated by the increasing rate of urbanization, in particular, in professional and educational fields of activity, where the accumulation of sanitary debris is surging to record heights, creating an environmental crisis that can no longer be ignored [4]. Disposable pads are the products of plastics, saturated chemicals, and synthetic fibers, are highly resistant to biodegradation. Several sanitary napkin disposal systems have also been developed to address the growing challenge of menstrual waste management in institutions and public places. Consequently, conventional waste management infrastructures remain ill-equipped to process these synthetic fibers, leading to long-term environmental accumulation [5, 6]. When disposed recklessly, buried shallow, drained in the drainage system, or burnt indiscriminately, such products cause long-term effect on the surrounding communities.

The use of disposable menstrual pads significantly increases the comfort of the user and helps him to comprehend more about personal physiological processes. Accordingly, the hygienic behaviors will become more uniform among different demographics [7]. However, the cities and schools also see a significant increase in the amount of waste that can be explained by this tendency [8]. Disposable products are a mixture of plastic, specialized paper and chemically intensive gels all resistant to standard landfill degradation protocols and none of which is dissolved [9, 10]. They are deposited by some users in open pits, others used to avoid trenches or towards latrine systems. Burning is used in exceptional cases and in this technique a partial combustion is achie

ved. Disposal of waste is associated with a distinct environmental cost. Combining these risks in a vicious circle contributes to the destruction of civilization that endangers both the health of the populace and the safety of ecosystems in general [10, 11].Improper management of sanitary waste also contributes to broader environmental sustainability issues associated with municipal solid waste management, particularly in developing countries [12].Improper management of sanitary waste also contributes to broader environmental sustainability issues associated with municipal solid waste management [13, 14]

Research has also shown how infrastructure limitations, especially the lack of disposal bins that belong to the privately owned individuals, have a direct impact on the choice of behavior that women make in dealing with menstrual management. In educational institutions that lack safe and healthy dumping systems and receptacles, adolescents are inclined to conceal the discarded items in the general rubbish and garbage, therefore, building a feeling of embarrassment and unwillingness to visit or participate in lessons [15]. These inclinations are evident in other cultural environments whereby women are not free to discuss menstruation at will, which is a setback in the use of waste containers [16, 17]. Besides, there are soil arrangements, mixed with municipal wastes, offering greater risks to workers in the sanitation sector, downstream sorting and processing a complicated task.

One of the weaknesses of handling menstrual supplies is the disposal. In the schools where good receptacles are not available, the wastes are normally buried by students under the desk or under the sleeves of their clothes. In places where infrastructure is down, it is replaced by secrecy [18, 19]. Lack of avenues of

disposal subjects many students into an academic withdrawal several studies have also reported that inadequate menstrual hygiene management negatively affects girls' school attendance and participation in education [19, 20].since they are more interested in hiding rather than studying to avoid embarrassment that may follow. Secondly any blood-stained objects that enter sewage accidentally put the sanitation workers at a risk and the fact that a certain number of them remains hidden in mixed waste make the separation process dangerous Improper handling of infectious waste also increases occupational health risks for waste handlers and sanitation workers [20].

Despite the changes in the modern society, where disposable pads have gained wider exposure, the long-term environmental impact of non-biodegradable menstrual waste and its safe disposal remains largely unaddressed and requires immediate intervention.

2. Experimental methodolgy

The present study focuses on the development of a small-scale sanitary napkin incinerator. The aim of the study is providing a safe and environmentally responsible disposal method. Methodology includes the entire process involving conceptual design to the unit's construction and performance evaluation. The system was designed to accommodate a heating chamber, temperature control system and a simple filtration system to provide controlled emissions and efficient burning. A careful selection of materials was made while fabricating the different components of prototype. Then, functioning of the incinerator, the effectiveness of control, residue management and maintenance requirements was discussed.

2.1. Design of incinerator

The incinerator’s designed was a compact, portable unit for safe disposal of sanitary waste. The major components of the design are a heating chamber, nichrome coil and an outlet linked to a filtration unit. The goal of this design is to obtain complete combustion, while limiting the emissions as much as possible.Waste-to-energy incineration systems with high energy efficiency have been intensively studied for a sustainable reduction in waste volume and recovery of thermal energy [21]. Proper airflow, sufficient temperature, and safe handling were taken in consideration during the design stage. The structure of the system is simple so that it can be easily used in institutions or households. The actual and well labelled model of incinerator is shown in Fig. 1.

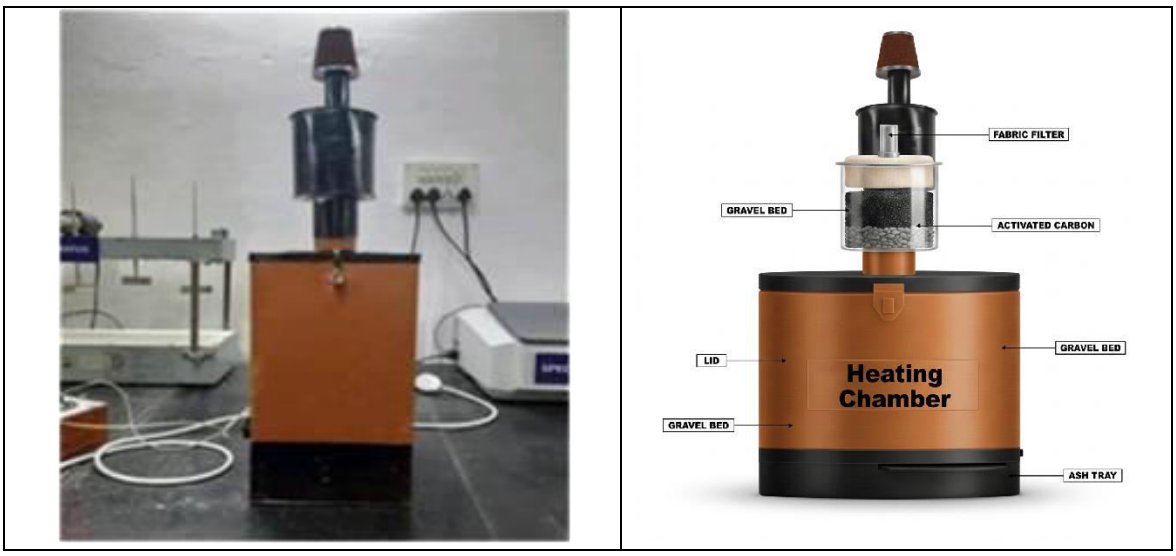


Fig.1. Actual and well labelled model of incinerator

2.2. Fabrication of incinerator

The fabrication process involved selection of suitable materials and then assembly of different components. The outer body was made using galvanized steel sheets to ensure durability and resistance to corrosion. The overall dimensions of the incinerator were approximately 61 cm in height, 10 cm in length, and 8 cm in breadth, making it compact and easy to handle and easy to use. It should be noted that the reported operating temperature of 800–1050°C corresponds only to the combustion chamber. The outer galvanized steel body was separated from the combustion chamber by an air gap, which minimized heat transfer and maintained the external casing at a substantially lower temperature during operation. Therefore, the galvanized outer body was not directly exposed to the combustion temperature.

The fabrication of the prototype was done step by step which includes cutting the sheets to a required dimensions, shaping, and welding them to form the main structure of the incinerator. After assembling the body, surface finishing and painting were done. The nichrome heating coil was installed inside the combustion chamber to provide the required heat.

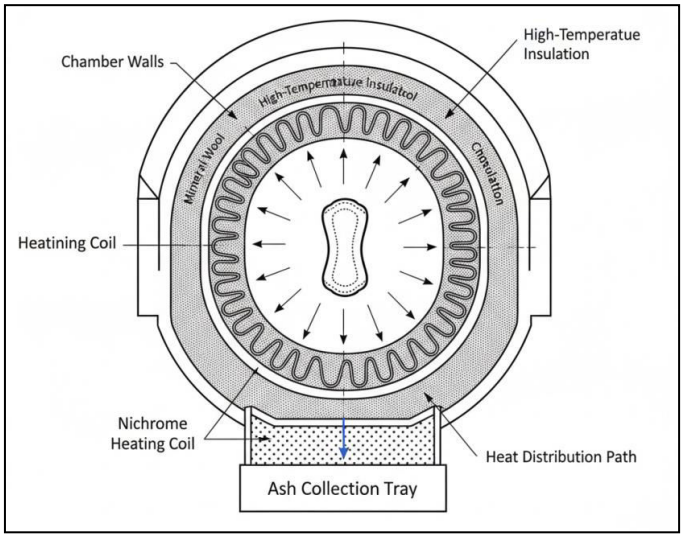


Fig.2. Combustion chamber cross-sectional view.

The cross sectional view of combustion chamber is shown in Fig. 2. A filtration unit was attached at the outlet in cylindrical form. It was filled in layers consisting of gravel at the bottom, activated carbon in the middle, and again the gravel on top.

2.3. Working of incinerator

The developed prototype, referred to as the "induction-heated" sanitary waste incineration system, employs a nichrome resistance heating coil as the heat source. Heat is generated by electrical resistance in the nichrome coil and transferred directly to the combustion chamber to achieve the required operating temperature. The incinerator works on the principle of electrical heating using a nichrome coil. When power is supplied, the coil generates high temperature inside the combustion chamber, which is sufficient to burn sanitary waste completely. The working incinerator is shown in Fig. 3. The combustion chamber was designed to accommodate up to 10 sanitary pads per cycle. However, the experimental trials reported in this study were conducted using 4–5 sanitary pads per cycle. Temperature is controlled using a simmer stat, which regulates the input voltage and maintains the desired heating conditions. In this process, the temperature ranges between 800 to 1050°C, depending on the material of the waste. It takes around 2 minutes to 15 minutes for

complete combustion. During this operation, the waste is placed inside the chamber, on the mesh plate above the nichrome heating coil for effective heat transfer and inductive combustion purpose and then, heat is applied until it is converted into ash, which is collected in the ash tray [22, 23]. The gases produced during combustion pass through the filtration unit, where harmful pollutants are reduced before being released into the atmosphere.



Fig.3. Working Incinerator

2.4. Operation and process control

Proper control of temperature and airflow is essential for efficient combustion of the incinerator. The simmer stat is used to adjust the temperature according to the amount and type of waste. Maintaining an optimum temperature ensures complete combustion and reduces the formation of toxic gases.

The filtration system plays a very important role in the process control by minimizing emissions. Adsorption-based materials such as activated carbon remain among the most effective media for capturing volatile organic compounds and other gaseous pollutants, and recent developments in advanced adsorbents further highlight the importance of adsorption technologies in environmental treatment systems [23] .Achieving proper emission control is very important, since the results of the tests conducted on the environmental performance of incineration systems are related to the combustion efficiency and the technologies used to remove pollutants [24, 25]. Regular monitoring of temperature and filter condition is required to maintain efficiency.The filtration system consists of gravel and activated carbon and was designed to reduce particulate matter and adsorb gaseous pollutants based on the adsorption characteristics of activated carbon. However, direct measurements of VOCs, dioxins, furans, or other gaseous emissions before and after filtration were not performed in the present study. Therefore, the emission reduction capability of the filtration unit was not experimentally verified and will be investigated in future work.

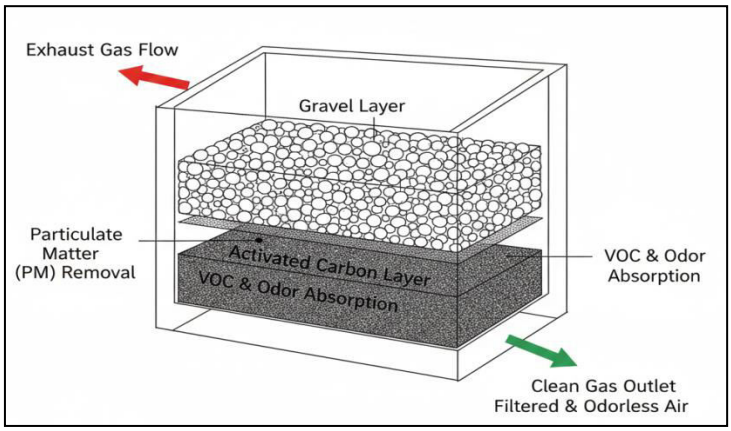


Fig.4. Emission control and filtration mechanism

2.5. Residue handling

After the combustion process, the remaining residue is collected in an ash tray placed at the bottom of the chamber. The residue is mainly in the form of ash, indicating effective burning of waste. It was observed that there is a significant reduction in weight it is around 90% or more, which confirms the efficient incineration.

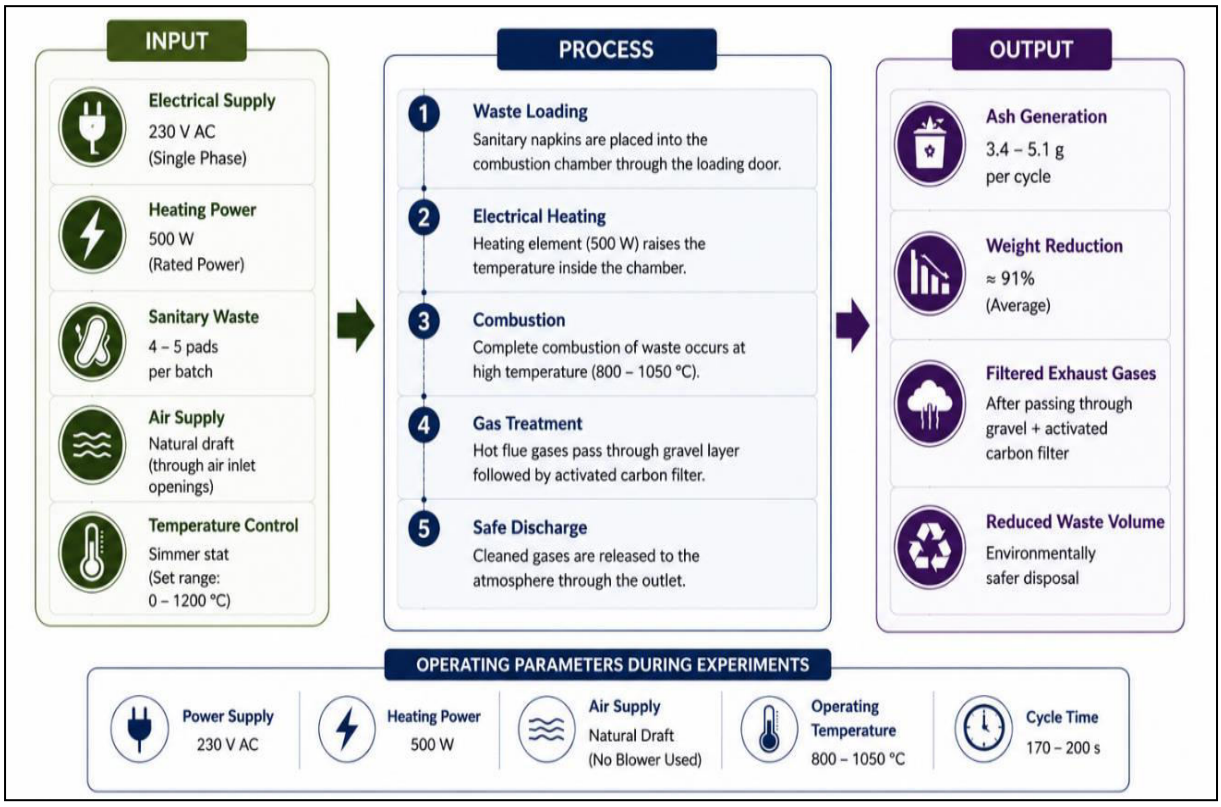


Fig.5. Input–process–output relationship of the developed sanitary napkin incinerator showing the operating conditions and performance obtained during the experimental study.

For the experiments, the operating parameters are a 230V AC power supply and 500W heating unit. It is represented in Fig. 5. The combustion air was introduced into the chamber through the inlets of the incinerator and the flue gases passed through the filtration unit before they are discharged. There was no blower or forced-air system used and the prototype was designed to run under natural draft. Thus, the air flow rate was not measured in the experimental study. These operating conditions were followed for all the conducted experimental trials. Fig. 5 presents a conceptual representation of the system inputs, processes, and outputs. Quantitative operating parameters such as electrical power input (W) and airflow rate (L/min or m^3/h) were not directly measured during the present investigation and are therefore not included in the diagram. Future studies will incorporate these measurements to enable a more comprehensive evaluation of the incinerator performance

2.6. Operation and maintenance

The incinerator is simple to operate and requires minimal training. Waste is inserted into the chamber, temperature is set using the control unit, and the process is allowed to complete. Regular maintenance includes cleaning of the ash tray, checking electrical connections, and replacing or cleaning the filter media when required.

2.7. zSafety features

The incinerator has been designed with simple safety features to ensure safe and secure operation when handling waste and burning it. The outer metal body stays insulated from the heating chamber, which minimizes the possibility of burns when using this product. The loading door has a heat-resistant handle to make it easier to open and close the chamber. The chamber should be left closed while the combustion cycle is taking place during operation. The ash is gathered in a removable ash collection tray at the bottom of the unit. The incinerator should be turned off and left to cool down before removing the ash. Then gloves may be used to remove the ash, and the ash can be disposed of following local waste management practices. No manual contact with the contaminated surface should be made when placing pads in the chamber. Waste should be regarded as being potentially infectious until it is properly burnt. Hence, the operator should use disposable gloves when handling the waste and wash his/her hands after operation. These are straightforward precautions to take to minimize the danger of burns, unintended exposures and exposure to pathogens when using these items. Based on published literature, temperatures in the range of 300–340°C are generally considered sufficient for thermal inactivation of many pathogenic microorganisms. However, no microbiological tests were conducted in the present study to experimentally verify pathogen destruction. Therefore, this statement is based on literature evidence rather than direct experimental validation. During laboratory testing, no visible damage to the galvanized outer body was observed. For long-term use, stainless steel is recommended for the combustion chamber.

During the laboratory-scale experiments, no visible degradation of the galvanized steel outer casing was observed. However, stainless steel is recommended for the combustion chamber in long-term or commercial applications because of its superior high-temperature resistance.

3. RESULTS AND DISCUSSION

The experimental results show the incinerator works effectively under controlled conditions. By adjusting the temperature, time, and waste quantity, proper burning of sanitary waste was achieved. It was observed that higher temperature and sufficient heating time led to faster and more complete decomposition, while the different pad materials showed slightly different burning behavior. A significant reduction in waste volume was seen in the form of ash, and the filtration system helped in reducing harmful emissions. Overall, the study confirms that proper operation improves efficiency and makes the system suitable for safe waste disposal. Careful record was taken of the use of electricity as efficient use of electrical energy is also an important performance parameter in thermal waste treatment systems [25]. Low ash residue means efficient combustion while incomplete combustion usually results in higher input of energy for complete oxidation [26].The observations supported the potential of the apparatus to process waste environmental soundly in an environment that does not have centralized disposal facilities.

3.1. Performance evaluation based on operating temperature and time

The test materials that were used to test the incinerator were offered a series of stringent test exercises wherein four or five extra pads were placed on each test to satisfactorily test the exact patterns of restroom usage [27]. The operating temperatures ranged between 800°C and 1050°C, which are consistent with the temperature range recommended for the safe thermal treatment of healthcare waste. Table 1 reflects a brief overview of the duration of combustion with respect to temperature. An increase in temperature makes the combustion rate faster, hence causing faster fibrils, gels, and polymer degradation. Even heat distribution reduces the amount of residual waste whereas systematic observation eliminates flare-up or partial burning, as observed in Fig. 6 indicating operating temperature vs combustion time.

Table.1 Performance Evaluation of Sanitary Napkin Incinerator

Trial No.	Number of Pads	Operating Temperature (°C)	Combustion Time (s)
1	4	800	210
2	5	850	195
3	5	900	180
4	4	950	165
5	5	1050	150

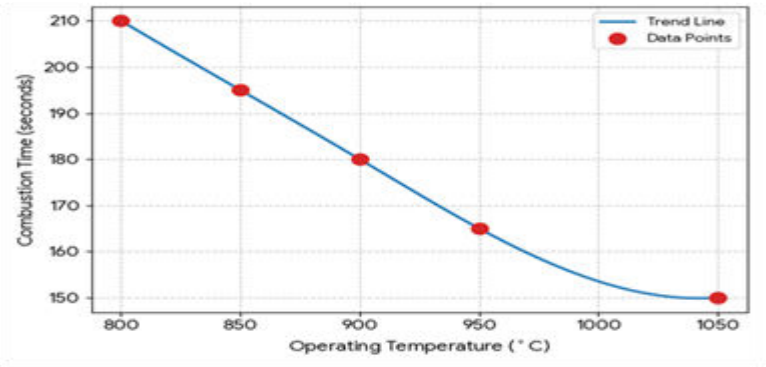


Fig.6. Operating Temperature vs Combustion Time

From Table 1 and Fig. 6 it is observed that, as the operating temperature increases, the combustion time decreases. At lower temperatures (800°C), the burning process takes longer, while at higher temperatures (up to 1050°C), the pads burn much faster. This happens because higher heat speeds up the breakdown of fibers and polymers present in the pads. The trend confirms that maintaining a higher and stable temperature improves the overall performance and efficiency of the incinerator.

3.2. Weight reduction and combustion efficiency

Weight loss was calculated by comparing pad mass before and after combustion. Table 2 shows the results of weight reduction for each trial combining different pad combinations, initial weight, final weight and ash weight.

Table.2 Weight Reduction and Percentage Reduction

Trial No.	No. of Pads	Initial Weight (g)	Ash Weight (g)	Weight Reduced (g)	% Weight Reduction
1	4	46.0	4.1	41.9	91.09
2	5	55.5	4.6	50.9	91.71
3	5	51.0	5.0	46.0	90.20
4	4	42.0	3.6	38.4	91.43
5	5	54.0	4.7	49.3	91.30

The empirical data show that there was about 91% weight reduction, which highlights how effective is the system when it is installed in limited architectural designs [28]. Comparative combustion experiment Lignocellulosic fibers and biodegradable polymer matrices were subjected to rapid pyrolysis, but their synthetic counterparts required high burning temperatures in the Puerto bottles. The fuller combustion which maximized the reduction of the particulate and gaseous emissions was also helped by the maximum

upwards-facing convective airflow . This 91% value represents only the reduction in waste weight. It should not be considered as energy saving. The energy performance is discussed separately in Table 6.

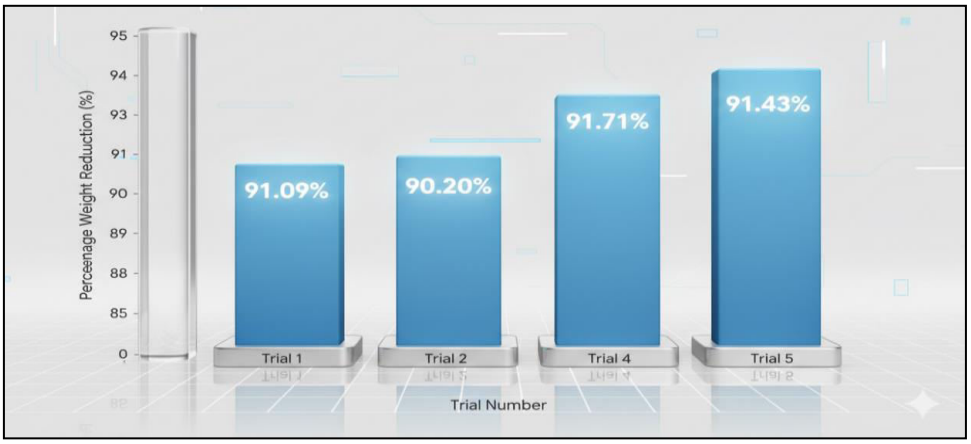


Fig.7. Percentage weight reduction across trials

The trials done on incineration gave consistent results of percentage weight reduction in Fig. 7, the highest value of weight reduction is 91.43%, with the weight of the waste being always reduced to greater than 90% limit. This consistency in non-sequential trials confirms the effectiveness of the sustained oxidation method, which demonstrates that it is a feasible and scalable solution to the rapid degradation of the sanitary debris in resource-limited settings [26, 28].

3.3. Rate of combustion and specific mass reduction

The combustion rate was derived from weight loss over time. It is represented in Table 3, while specific weight reduction per pad evaluated scale-up potential is indicated in Table 4.

Table.3 Rate of Combustion

Trial No.	Weight Reduced (g)	Time (s)	Combustion Rate (g/s)
1	41.9	210	0.20
2	50.9	195	0.26
3	46.0	180	0.26
4	38.4	165	0.23
5	49.3	150	0.33

The fact that the rate of combustion increased with temperature in the range of 0.20-0.33 g/s testifies to the fact the process was accelerated as the amount of heat input increased. Mean loss of specific weight of 9.86g/pad is a desirable metric of waste-handling capacity and an indicator of the scale-up of the system in future.

The results of the comparative combustion rates during different experimental runs (Fig. 8) support the effectiveness of the incineration unit in maintaining elevated speeds of the combustion. In the five experiments, the burn rate was between 0.20g/s and 0.33g/s. These findings indicate that through the optimization of the operating environment, the system can enhance the degradation of organic materials significantly, hence, improving the amount of material that the treatment unit can process in a day [27, 28].

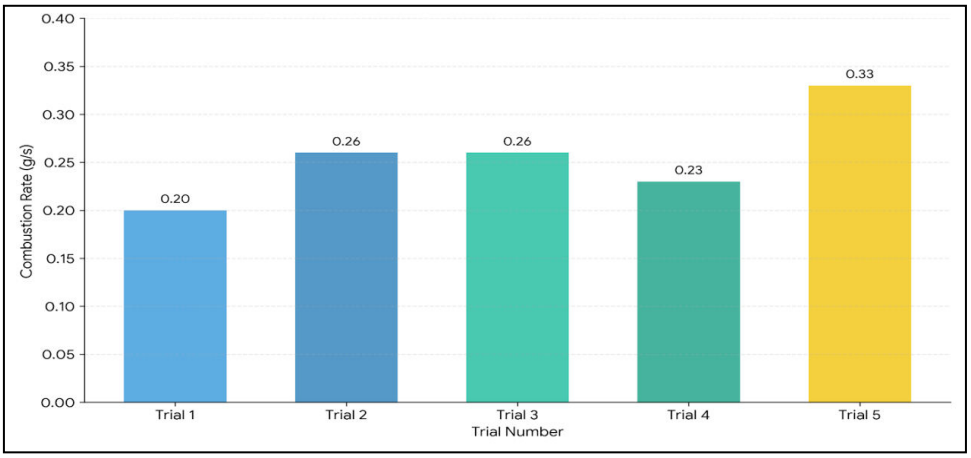


Fig.8. Comparative combustion rates recorded during experimental runs.

Table.4 Specific Weight Reduction per Pad

Trial No.	No. of Pads	Weight Reduced (g)	Reduction per Pad (g/pad)
1	4	41.9	10.48
2	5	50.9	10.18
3	5	46.0	9.20
4	4	38.4	9.60
5	5	49.3	9.86

The values shown in Table 4 are the mean for each experimental batch in this study, for weight loss per pad. This parameter was added for the purpose of offering a simple indication of the treatment capacity of the developed incinerator with the tested conditions. The amount of reduction will vary depending on the composition, thickness, absorbent capacity and original weight of sanitary napkins, and should not be fixed for any commercial product. The combustion characteristics of different brands were different as shown in Table 5, due to the different material composition of various brands. The data given in Table 4 are thus only representative for the pads investigated in the present study.

Higher combustion rates were observed at elevated temperatures, confirming the direct relationship between thermal input and oxidation speed.

3.4. Brand-wise combustion characteristics

The various commercially brands of the sanitary napkins were experimented to determine the influence of the material composition on the combustion behavior. The comparative results are presented in Table 5. The trials were carried out in a lab-fabricated sanitary napkin incinerator to observe how different brands burn under controlled conditions. It was observed that pads made from natural fibers burned faster and required lower temperature, while pads with more plastic and chemicals took longer and needed higher heat. The incinerator worked properly for all types, but more time and energy were required for plastic-based pads. These trials clearly showed that material composition plays an important role in combustion behavior. The observed differences in combustion behavior among the tested sanitary napkin brands may be attributed to variations in material composition and product design. However, as only one experimental trial was conducted for each brand, this observation is preliminary and requires further validation through replicated experiments and detailed material characterization.

Table.5 Brand-wise Combustion Characteristics of Sanitary Napkins

Brand Name	Material Composition	Effective Temperature (°C)	Combustion Time (s)
Nua	Organic cotton fibers	800	90
Saathi	Banana fiber + biodegradable polymers	820	110
Sirona (Reusable Cloth)	Multi-layer cotton fabric	850	140
Whisper Ultra Clean	Wood pulp + SAP + PP sheet	900	170
Stayfree Dry Max	Gel-based SAP + polymers	950	210
Sofy Antibacterial	Chemically treated polymers	1000	240
Plastic-based Pad	Polyethylene & polypropylene	1050	300

3.5. Energy-specific mass reduction

Table 6 shows the amount of waste treated per unit of energy, where efficiency is calculated as the ratio of weight reduced to energy consumed.

Table.6 Energy-Specific Mass Reduction

Trial No.	Time (s)	Energy Used (kWh)	Weight Reduced (kg)	Reduction (kg/kWh)
1	210	0.12	0.0419	0.35
2	195	0.11	0.0509	0.46
3	180	0.10	0.0460	0.46
4	165	0.09	0.0384	0.43
5	150	0.08	0.0493	0.62

The overall efficiency showed some improvement from Trial 1 to Trial 3, but a decrease was noted in Trial 4 and a maximum in Trial 5. This difference may be attributable to the slight difference in composition of the sanitary pad used and its original weight and slight differences in the arrangement of the sanitary pad in the combustion chamber. These can affect the distribution of heat and the combustion characteristics, leading to slight variations in the efficiency of weight reduction. The slight reduction in efficiency observed during Trial 4 was not associated with any intentional change in the operating conditions. This variation is likely due to minor experimental factors, such as differences in sanitary pad composition, moisture content, loading arrangement, or normal combustion variability encountered during laboratory-scale testing. As the decrease was observed in only one trial and the efficiency increased again in Trial 5, it is considered an isolated variation rather than a systematic performance trend. Further replicated experiments are required to establish the statistical significance of such variations.

The results indicate that an explosive burning process can instantly cut cotton into ash. With a small amount of heat and a short amount of time, the cotton is turned into ash [26, 27, 28]. Synthetic padding, in comparison, has significantly greater thermal resistance, which is due to the high-density polymer matrix and cannot withstand pyrolysis as long in the flame.

In order to obtain sufficient breakdowns of such materials, increasingly high temperatures should be used continuously. Combustion byproducts escape mostly as a dense smoke when the temperature fails to turn to

the required level instead of evaporating in a clean manner. Hence, close management of the flame is critical; failure of which results in emission of poisonous aerosols to the immediate environment.

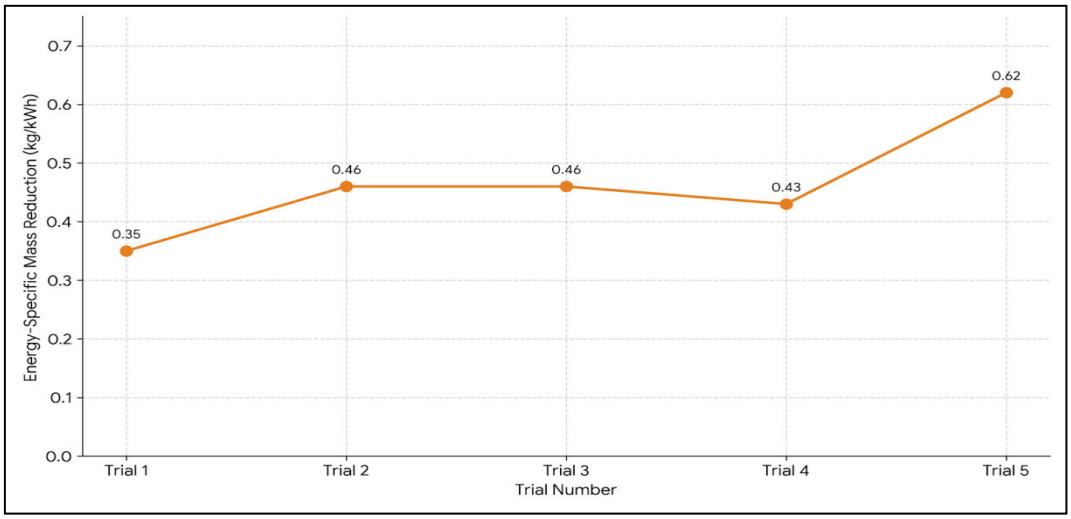


Fig.9. Energy-Specific Mass Reduction Efficiency

From every-specific mass reduction (kg/KWh) varying between 0.35 and 0.62 Kg (as illustrated in Fig. 9), the visible depletion of waste material serves as clear proof of the incinerator's performance and power usage. The efficiency is evident in the situation whereby destruction occurs without consuming an excessive amount of electricity and most especially in compact units that are powered by current alone.

The results obtained from Table 6, indicates that better efficiency is achieved at lower energy input with proper control of burning time. During trials in the lab-fabricated incinerator, cotton-based materials burned quickly and converted to ash in a short time, while synthetic pads showed higher resistance and needed more heat. Inappropriate temperature maintenance led to dense smoke if it occurred during the burning. So, it's essential to have the proper and adequate operating temperature. The efficiency of the lab fabricated sanitary napkin incinerator (kg/kWh) obtained clearly indicates the change in efficiency with the different trials of the incinerator (Fig. 9). One can see that the efficiency improves as the trials go on, then decreases slightly in trial 4, and peaks at Trial 5. This demonstrates that the more tightly the operating conditions (e.g., burning time, temperature) are controlled, the better the performance. Trial 5 gives the best results and is the most efficient use of energy and minimum waste. Overall, the trend demonstrates that adjustments to the incinerator to create a proper setting result in a more effective and cleaner combustion.

3.6. Comparison with previous studies

The sanitary napkin incinerator developed was evaluated and compared with the similar small scale incinerators reported in literature. The developed system resulted in a weight reduction of around 91% (Table 7), which is similar to that reported in the previous studies. The combustion time was similar to that reported for small capacity sanitary waste incinerators. In addition, the fuel consumed was relatively low with the 500 W heating unit and about the same combustion efficiency was achieved. The results show that the prototype developed is as performance as any of the prototypes existing and simple and economical too in use in decentralized applications. Table 7 is used to make the comparison. The data presented in Tables 1-6 are from five tests conducted under the same operating conditions. Standard deviation could not be computed because repeated experiments were not carried out. Repeated trials and statistical analysis will be conducted in the future. The approximate cost of fabrication of the prototype was INR 8,000 – 12,000 and

the cost of electricity used in the operation of the prototype was INR 2-4 per cycle depending on the operating time and the local electricity tariff. This enables the system to be used in low-resource and decentralized contexts.

Table.7 Comparison with previous studies

Study	Combustion Time	Weight Reduction	Energy/Power	Remarks
[25]	3–5 min	85–90%	1000 W	Electrically heated unit
[26]	4–6 min	88–92%	750 W	Small-scale sanitary waste incinerator
[27]	5 min	80%	800 W	Combustion unit
[28]	4 min	85%	700 W	Small disposal unit
Present Study	170–200 s	≈91%	500 W	Low-cost prototype

Although the experimental results demonstrated consistent trends across the five trials, further replicated experiments are required to statistically validate the repeatability and reliability of the reported performance

3.7. Practical limitations

The main goal of this study was to test the combustion performance of the developed sanitary napkin incinerator. The present study was limited to the assessment of the combustion performance developed prototype only. This work did not include a detailed emission analysis, such as the measurement of VOCs, dioxins, furans, particulate matter and other combustion gases before and after the filtration unit, which will be taken into account in future investigations. In the present work, ash characterization was not considered. Hence, chemical composition of the ash and presence of unburned materials and other contaminants were not investigated in the ash residue. Thus, in this study the safety of ash for disposal was not tested. Further studies will include a detailed ash characterization to determine the composition of the ash and to determine its suitability for disposal as per applicable environmental guidelines. Furthermore, all the trials were performed with only one type of sanitary napkin of each brand. So, the comparison with the brands is preliminary and further study will involve repeated experiments. The performance data reported in Tables 1-6 are from five separate experimental trials with the same operating parameters. No repeatability analysis, no standard deviation and no confidence interval could be obtained because repeated measurements were not made for each operating condition. The combustion time, weight loss, and energy used were found to be fairly consistent for all of the trials, indicating a fairly consistent operation of the prototype; however, these results should be viewed as preliminary. Replicate experiments and statistical analysis of the results will be conducted in the future to ensure the repeatability and reliability of the incineration system developed in this study. Microbiological analyses to verify pathogen destruction were not performed. Future studies will include microbiological testing to experimentally confirm pathogen inactivation during the incineration process.

4. Conclusion

The current paper demonstrates that small sized incinerators of sanitary napkins can be an appropriate, low-resource decentralized method of menstrual waste management. The effect of the device in processing sanitary pads, as shown through experimental analysis, was the ability to process between 5-10 Sanitary pads in one cycle at a burning time of 170-200 The process yielded a 91% mass reduction with only 3.4–5.1 g of ash remaining per test, effectively proving the system's ability to achieve full oxidation.

The equipment was continuously maintained at temperatures of 800°C to 1050°C, the heating of the apparatus was also by nichrome heating coil, and as a result, allowed the transmission of thermal energy in the most precise manner, thus enhancing the decomposition processes and minimizing the use of electricity. Moreover, filtration unit was successfully introduced to reduce the visible emissions and, as a result, the prototype was found to be potentially useful to reduce environmental and occupational risks with regard to small-scale garbage burns.

Approximate fabrication cost of the prototype was INR 8,000–12,000, while the operating electricity cost was about INR 2–4 per cycle depending on operating time and local electricity tariff. This makes the system suitable for decentralized and low-resource settings.

The high level of portability, low level of infrastructural reliance, and certain easy-to-use features make the prototype viable in educational setups, health facilities, dormitory, and community cozy area centers, especially in areas where municipal infrastructure facilities to handle garbage are either limited or absent. The data during operation confirmed the stability of the system, and it helped to control the changes in load during the process, which was also a demonstration of the applicability of the system in the scaled implementation process without overloading the local power system. The results indicate that the use of energy-efficient heating systems, precise control of air flow, and efficient and effective filtration, offer a safe, effective and environmentally friendly approach to waste treatment.

The research provides evidence-based solutions to decentralized incineration systems thus helping to achieve progress in the area of the health, clean management of waste and ecologically friendly environmental practices.

Abbreviations

- **SAP** – Super Absorbent Polymer
- **PP** – Polypropylene
- **PE** – Polyethylene
- **MSW** – Municipal Solid Waste
- **kg/kWh** – Kilogram per Kilowatt-hour
- **g/s** – Gram per second
- **°C** – Degree Celsius
- **V** – Volt
- **A** – Ampere
- **s** – Second
- **g** – Gram
- **cm** – Centimeter

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Prospect of Using Genetically Modified Plants in Constructed Wetlands for Wastewater Treatment

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Abstract

Constructed wetlands (CWs) are built to work like natural wetlands. They can remove pollutants from wastewater through physical, chemical, and biological processes. Commonly occuring wetland plants often have limited ability to take up pollutants, especially heavy metals. This is because, they do not have the advanced mechanisms found in transgenic plants. Conventional plants also find it difficult to break down hazardous organic contaminants, making them less effective against complex industrial pollutants and persistent substances. Genetically modified macrophytes, however, can be enhanced with genes that improve capacity to uptake metals, tolerate stress, and to break down pollutants. These improvements enable better contaminant removal, even under tough conditions. They also widen the range of pollutants that can be treated, all while keeping the wetland's structure intact. This paper reviews currently ongoing researches on using genetically modified (GM) plants in constructed wetlands, drawing from sources like ScienceDirect, ResearchGate, and Elsevier, and using keywords such as 'genetically modified plants', 'constructed wetlands' and 'wastewater treatment.' The review also includes official documents from India and other countries. It prominently shows the proven and likely benefits in treatment efficiency, examines ecological and biosafety risks of releasing transgenic macrophytes, and points out knowledge gaps and future research priorities.

Keywords

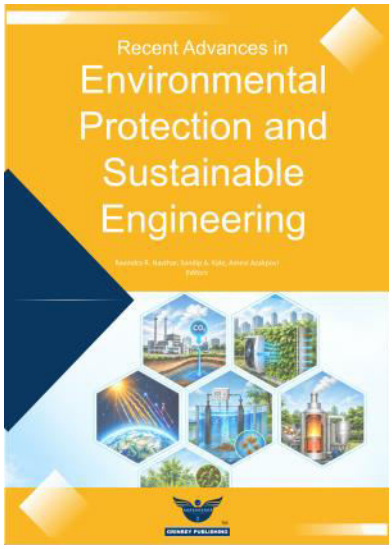
Constructed wetlands; genetically modified plants; xenobiotic degradation; pollutant removal.

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1. Introduction

The term ‘Constructed wetlands’ denote engineered treatment systems that imitate the structure and function of natural wetlands for the purpose of removing contaminants from wastewater in a cost-effective and environmentally sustainable manner. These constructed wetlands depend on the overall action of plants, microorganisms, and substrates to remove pollutants by utilising physical, chemical, and biological processes. Constructed wetlands utilise some important pollutant removal mechanisms, which are as follows: sedimentation and filtration of suspended solids; microbial degradation and transformation of organic matter and nutrients; adsorption and precipitation of contaminants onto substrates; and plant uptake and storage of nutrients and selected pollutants. These processes, when combined, help the constructed wetlands to treat municipal, industrial, and agricultural wastewater while delivering additional ecosystem services, such as habitat creation and landscape enhancement [1]. Traditional constructed wetland systems predominantly employ indigenous or well-adapted wetland plants, including emergent species such as Typha, Phragmites, Scirpus, and Cyperus. These plants are selected because they can tolerate waterlogged, anoxic soil conditions where ordinary land-plants would fail. These plants have extensive fibrous root systems that play an important role in wetland treatment performance by stabilising the substrate, promoting sedimentation, and creating microscale redox gradients. Oxygen release which occur from roots into the rhizosphere, improves aerobic microbial activity, supporting processes such as nitrification, while adjacent anoxic zones support denitrification and other anaerobic transformations. Additionally, the macrophytes break down nutrients such as nitrogen and phosphorus into their biomass, thus acting as a temporary sink that helps reduce nutrient concentrations in the treated effluent [2, 3]. Despite the effectiveness of conventional plant-based systems, they also have some essential limitations. The process of uptake of essential nutrients by plants is often seasonal, controlled by growth cycles and climatic conditions. Long-term pollutant removal depends heavily on microbial and substrate-mediated processes rather than on plant assimilation alone. It has been observed that many wetland plants show limited tolerance to high contaminant loads, salinity, drought, or toxic industrial effluents. This phenomenon can reduce system efficiency under extreme or variable operating conditions. Latest innovations in biotechnology and genetic engineering have created new possibilities for improving the performance of constructed wetlands by using engineered plants with modified or enhanced properties. Genetically modified plants can be designed so as to exhibit improved phytoremediation, including increased uptake and accumulation of nutrients, heavy metals, or organic pollutants. Increasing root exudation patterns may stimulate beneficial microbial communities, hence strengthening coupled plant–microbe remediation pathways. In addition, genetically modified plants can be modified for greater resistance to abiotic stresses, including salinity, drought, and changing water levels. This, in turn, allows wetlands to function more reliably under tough environmental conditions. If such engineered plants are introduced, it can have the potential to increase sustained biomass production, improve contaminant removal efficiency, and expand the applicability of constructed wetlands across a wider range of wastewater types and climatic regions [4]. However, their use also generates essential ecological and regulatory considerations. This can include biosafety, gene flow, and long-term impacts to the ecosystem. Consequently, biotechnology offers promising opportunities to enhance constructed wetland systems. But its application must be guided by meticulous risk assessment and integrated system design to ensure environmental sustainability [1, 5-8].

2. Role of Plants in Constructed Wetlands

The large aquatic plants, commonly grown in constructed wetlands, are called macrophytes. These plants are vital to treatment performance as well as hydraulic and habitat functions. These plants used in constructed wetlands carry out several important functions. Solar energy is captured by chlorophyll during photosynthesis. The carbon dioxide is captured by these plants from the atmosphere. By utilising this solar energy, these macrophytes assimilate this inorganic carbon from the atmosphere into organic molecules such as glucose,

carbohydrates and other biomass. This phenomenon supplies the energy source for bacteria and fungi. These macrophytes also cause a reduction in wind speed near the water surface. Dense wetland vegetation reduces light penetration in the water column. The limited light suppresses the growth of phytoplankton, since these phytoplankton depend on sunlight for photosynthesis. The presence of these plants in constructed wetlands also reduces water flow velocity, which creates better conditions for sedimentation of suspended solids and also increases the contact time between water and the plant surface areas. These macrophytes play an important role in stabilising the soil surface of the constructed wetlands, since penetration of their root systems reduces the formation of erosion channels [2] (Brix, 2003). In vertical flow constructed wetlands, the growth of roots of these plants helps to reduce clogging [9]. The submerged stems and leaves of macrophytes provide a surface area for the development of biofilms and also the growth of photosynthetic algae, bacteria and protozoa [10]. Similarly, the roots and rhizomes, buried in the soil, also support attached growth. These biofilms help in organic matter degradation and nutrient transformations [9]. The roots of the emergent and submerged macrophytes leak oxygen into the rhizosphere. This creates oxidised microsites in the anoxic media, which in turn stimulates aerobic degradation of organic matter and nitrification [8, 11]. Roots exude organic compounds (often estimated as a fraction of fixed carbon), which can serve as electron donors for denitrifiers, thereby supporting nitrate removal in anoxic microsites of subsurface-flow wetlands [3, 9]. Ammonium, nitrates and phosphorus are assimilated by the plants into their biomass. The emergent macrophytes are capable of storing a considerable amount of nitrogen and phosphorus per m2. Their nutrient uptake capacity ranges between 30 and 150 kg P per hectare per year and between 200 and 2500 kg N per hectare per year [5, 11]. The emergent and rooted floating-leaved macrophytes absorb inorganic nitrogen (both ammonium and nitrate) from porewater in the root zone; free-floating macrophytes take up N directly from the water column. The long-term removal of phosphorus is mainly accomplished by sorption / precipitation onto the substrate . Phosphorus uptake occurs mainly as orthophosphate, taken up primarily through roots from sediments or substrates. Uptake via leaves and stems is generally limited in emergent species, but becomes more important in submerged macrophytes, which can directly assimilate phosphorus from the surrounding water. Also, the phosphorus uptake through submerged leaves and stems is generally smaller, except in submerged species [2, 12]. A study conducted on constructed wetland macrophytes reported nutrient uptake ranging from 8.6–9.3 g Total Phosphorus and 29.1–48.2 g Total Nitrogen for the tested species in the experimental units. This data shows that the nutrient uptake varies strongly with species and biomass production. Macrophyte species can notably affect ammonia and phosphorus removal, with one laboratory study reporting up to 82% ammonia removal and 76% soluble phosphorus removal in Cyperus papyrus[13, 14].

Genetic modification can make wetland macrophytes much more useful and tolerant to harsh conditions, by giving them stress tolerance, better resource use, and targeted pollutant-removal abilities. By adding genes for drought and salt tolerance, improved root systems, or stronger antioxidant defenses, GM plants can keep taking up water and nutrients, and maintain healthy growth, even when conditions are tough. They need less fertilizer because they use nutrients more efficiently. These stress-tolerance characteristics help macrophytes survive in wastewaters with high metal content, salt, or other harsh conditions, and they also support long-term wetland treatment [4, 15-18]. Genetic modifications can also directly improve pollutant removal. For example, boosting genes for metal transport or detoxification increases the plant's ability to extract heavy metals. The breakdown or transformation of toxic substances can be done by adding bacterial enzymes . Other changes, like increment of root surface area or release of more root exudates, can stimulate helpful microbes in the soil. Together, these improvements speed up microbial processes like nitrification, denitrification, and organic matter breakdown. As a result, constructed wetlands with GM macrophytes can remove tough pollutants more effectively, while also reducing the need for pesticides and machinery, lowering nutrient runoff, preserving soil, and supporting more sustainable treatment and land use.

3. Assessing the Nature of Genetically Modified Plants

With the emergence of Genetically Modified (GM) plants, there was a considerable transformation in modern biotechnology. These GM plants, on one hand, improved several deficiencies of normal plants, while on the other hand, they also introduced some problems. Hence, before introducing the engineering application of these plants, it becomes essential to investigate their beneficial uses as well as disadvantages.

3.1. Advantages

Genetically modified plants can be prepared to tolerate abiotic stresses such as drought and salinity, which can normally restrict plant growth and their productivity. These stresses disrupt water uptake, nutrient balance, and cellular metabolism in conventional plants. Genetic engineering may incorporate certain genes that confer stress tolerance or can enhance plant performance under adverse conditions. These types of modifications may increase water usage efficiency, cause improved root structure, or enhance osmotic adjustment within plant cells[4, 18]. Saline ecosystems have the capacity to control ion transport functions, that help to lessen toxic sodium accumulation while preserving ionic balance. The genes capable of tolerating stress also help protect cellular elements by activating antioxidant and protective pathways. Due to this, some important physiological processes such as photosynthesis and respiration continue to function effectively. This helps GM plants to carry out normal growth and biomass production even under limited water availability or high salinity. So, these plants can be cultivated within environments that would otherwise be unsuitable for conventional crops. If there are observed improvements in nutrient use efficiency through genetic modification, then it allows GM plants to assimilate nitrogen, phosphorus, and micronutrients more effectively. This reduces fertiliser requirements and minimize nutrient runoff into water bodies. Insect-resistant and disease-resistant GM plants often require significantly reduced chemical pesticide use, thereby lowering agricultural input costs and mitigating environmental contamination from insecticide residues. Herbicide-tolerant GM crops can help in more efficient and selective weed control, thereby allowing farmers to adopt eco-friendly farming practices, preserving soil structure, reducing soil erosion and enhancing carbon sequestration, causing diminished reliance towards mechanical farming practices [18, 19]. In constructed wetlands, GM plants may also provide direct treatment advantages by improving the uptake, translocation, and sequestration of heavy metals. Literature on wetland grasses and transgenic phytoremediation shows that introducing genes such as merA and merB, metal transporters, phytochelatin-related genes, or metallothionein pathways can enhance tolerance to toxic metals and increase remediation potential. This is particularly relevant for wetlands treating metal-bearing industrial effluents, where plant-assisted phytoextraction can complement sorption and substrate-based removal processes [4, 17, 18].

Another major advantage is improved breakdown of organic pollutants and xenobiotics in the rhizosphere. Some GM plants can be designed to express degradative enzymes in their tissues or roots. These enzymes can act on the pollutants directly, by oxidising, hydrolysing, or transforming contaminants into less harmful forms. Again, some other GM plants can stimulate microbial activity through greater root surface area, altered exudation, and enhanced oxygen release into the rhizosphere. However, many field studies have exhibited that the effect is often small or inconsistent, with soil type, season, and crop management usually having stronger influences than the GM trait itself. All these changes can promote aerobic degradation, nitrification, denitrification, and mineralisation of recalcitrant compounds, while also improving microbial colonisation on roots and litter surfaces [4,16,17].

3.2. Disadvantages and Challenges in Using Genetically Modified Plants in Constructed Wetlands

Despite their increased remediation potential, genetically modified (GM) plants in constructed wetlands for wastewater treatment present several significant disadvantages, which makes it hard for their wider acceptance and application as depicted in Figure 1.

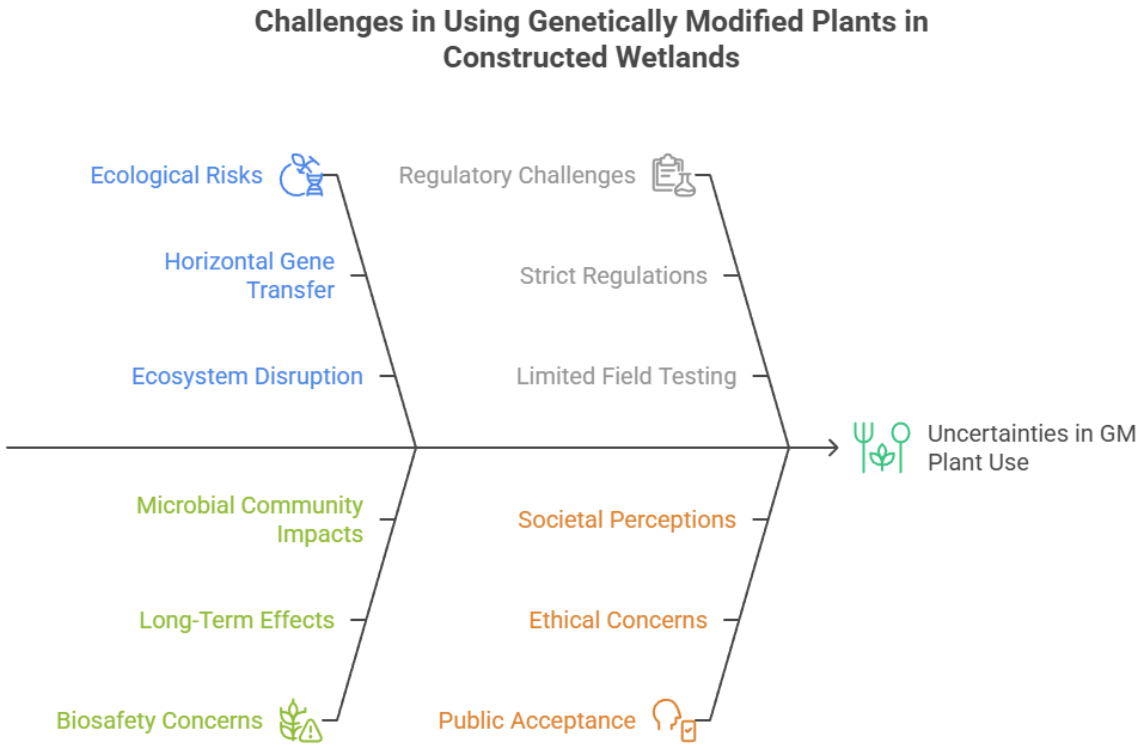


Fig. 1. Disadvantages and Challenges in Using Genetically Modified Plants in Constructed Wetlands

The primary concern is horizontal gene transfer (HGT), where transgenic DNA can be transferred onto non-target organisms including soil bacteria and wild plant relatives through transformation, conjugation, and transduction, potentially spreading antibiotic resistance genes used as selection markers [20, 21]. Cross-pollination can be prevented by using buffer zones between the GM and the non-GM plant of the same species. In genetically modified wetland plants, mitigation of horizontal gene transfer should integrate buffer zones, reproductive sterility, rhizome containment, and hydrological isolation to prevent spread within wetland landscapes. For example, in case of Phragmites australis and Typha latifolia, which can produce abundant wind-dispersed pollen and spread aggressively in wetland systems, we can observe that reproductive containment is especially important. For Canna indica, vegetative spread and site hygiene may be relatively more relevant than long-distance pollen movement, although both should still be considered. Biosafety risks are still not fully understood, as long-term ecological effects are not fully characterised, including adverse impacts on indigenous microbial communities important for nutrient cycling and wetland ecosystem functioning [22]. The persistence of transgenic DNA within aquatic environments poses additional concerns, as naked DNA from dead or damaged GM plant cells can remain intact when associated with sediment particles, creating opportunities for uptake by naturally competent bacteria in wastewater systems [21]. The major hurdles to GM plant deployment in phytoremediation programs are due to regulatory as well as public acceptance challenges, including strict biosafety regulations and limited field-testing permissions. The growth-stage-dependent effects of GM plants on microbial communities introduce inconsistency in treatment performance, as transgene expression varies seasonally and with plant development stages, affecting pollutant removal efficiency [20]. Additionally, antibiotic resistance marker genes may promote the development of resistant bacterial strains in biofilms and microbial communities within constructed wetlands under normal wastewater treatment stress conditions [21, 22].

4. Opportunities and threats of using genetically modified plants in Constructed Wetland Systems

There are several benefits due to the adoption of GM plants in constructed wetlands for treatment performance and system design. GM plants can be modified with genes that increase the uptake, sequestration, or metabolic breakdown of specific pollutants (e.g., heavy metals, nutrients, pesticides), hence improving removal efficiencies for target contaminants. In addition, enhanced stress tolerance allows wetlands to function under more contaminated, saline, or hydraulically variable conditions without notable loss of treatment efficiency. For a given effluent quality target, more efficient pollutant removal may reduce the required hydraulic retention time, overall system size, and associated land footprint. GM plants may also be designed to simultaneously support water purification, bioenergy or biomass production, and nutrient recovery, helping to enhance the value of the resource. Taken together, these traits suggest that GM plants could enable more compact, resilient, and multifunctional constructed wetland systems [7, 23].

Although it looks promising, a rigorous appraisal is required before deploying genetically modified plants in wetlands, due to several concerns. Outcrossing with wild relatives or the escape of transgenes may lead to unintended consequences, such as the creation of "superweeds" or altered interactions with non-target species [18]. Genetically modified plant species might disrupt microbial communities, food webs, or ecosystem processes within and beyond the wetland [24]. The fate and impact of transgene products such as Bt toxins in aquatic systems remain areas of limited study. Additionally, there might be unintended effects on non-target organisms in the treatment system, likely disruption of beneficial microbial communities essential for pollutant degradation, and regulatory issues regarding environmental release[4]. With respect to regulatory and public endorsement, the deployment of GM plants in open aquatic settings may create societal, ethical, and policy challenges [12, 25]. Public acceptance poses a major challenge towards incorporation of GM plants, since perceptions about GM plants differ between various countries regarding the importance and the associated risks. Several nations show reluctance towards using GM products, while companies prioritise profits beyond potential long-term problems. The ethical challenge is mainly regarding the interference with natural life processes, which raises the question of how to balance technological advantages against ecosystem integrity [24-26]. These concerns demand strict risk assessment protocols before deploying GM plants in wetland remediation applications.

5. Current Research and Prospects

As of now, genetically modified (GM) plants for constructed wetlands are mainly at the conceptual or mesocosm research stage, drawing heavily on more extensive transgenic phytoremediation work rather than full-scale CW applications. Current research focuses on introducing genes that can improve the performance of metal uptake, sequestration, or detoxification, as well as enzymes that speed up the degradation of organic pollutants like pesticides and industrial chemicals. Studies show markedly improved accumulation or transformation of target contaminants in soil and water systems, suggesting clear potential if these plants are integrated into CW hydraulics and configurations. The concept of using GM plants for augmented phytoremediation is scientifically feasible, though large-scale field data remain limited [11]. Risk assessment frameworks are being proposed to evaluate gene flow, ecological impacts, and monitoring strategies [12, 19]. To date, there is no specific regulatory framework worldwide that provides guidelines for using these GM plants in constructed wetlands for treating wastewater. Instead, each country follows its own rules regarding GMO biosafety, using GM plants on a case-by-case basis, with risk assessments for environmental safety, gene flow, and ecosystem impact. These GMO biosafety rules are a set of scientifically regulated management measures that are used to assess and minimise possible risks from genetically modified organisms to human health, animals, and the environment. For example, in the European Union, releasing genetically modified plants into nature requires strict approval under Directive 2001/18/EC, including safety checks and monitoring. This directive controls any outdoor release of modified plants, and for its introduction, official

permission, risk studies, and ongoing safety checks are essential. In case of India, genetically modified plants fall under general environmental laws, but till now there exists no specific rule for genetically modified wetland plants, meaning they need special case-by-case clearance. Although India in 2016 published a guideline document about the Environmental Risk assessment of Genetically Engineered Plants, but it is a general biosafety guidance for environmental release of GE plants, and has no mention about the prospects of using these genetically modified plants in a constructed wetland for wastewater treatment[27-29]. Current studies have shown that, the conventional constructed wetlands are cost-effective in comparison to the conventional treatment methods in a sewage treatment plant.GM plants may only be thought of in place of conventional macrophytes if they significantly outperform natural species in nutrient uptake and resilience. Cost involved in their research & development (R&D), biosafety concerns, and regulatory hurdles are at present quite high[30]. Thus, in spite of being superior in nutrient uptake capacity and resilience characteristics, their high initial R&D costs, ecological and regulatory risks and also unproven-ness does not make them attractive to be used in constructed wetlands till now.

6. Conclusion

Constructed wetlands offer a resilient, environmentally friendly solution for wastewater treatment, with macrophytes, substrates, and microbial communities working together to remove contaminants. The assimilation of genetically modified plants into these systems presents a promising option to enhance pollutant uptake, stress tolerance, and treatment efficiency, potentially reducing land requirements and expanding the range of treatable wastewater. However, questions regarding horizontal gene transfer, ecological impacts, and public and ethical acceptability point out the need for precaution. Future progress will depend on rigorous, long-term field studies, transparent risk–benefit evaluations, cost-effectiveness and the development of clear regulatory and monitoring frameworks before large-scale implementation.

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