Final Report

Status Report on Best Practices and available Nature-based Solutions for supporting Air Pollution mitigation in the South and South-East Asian region

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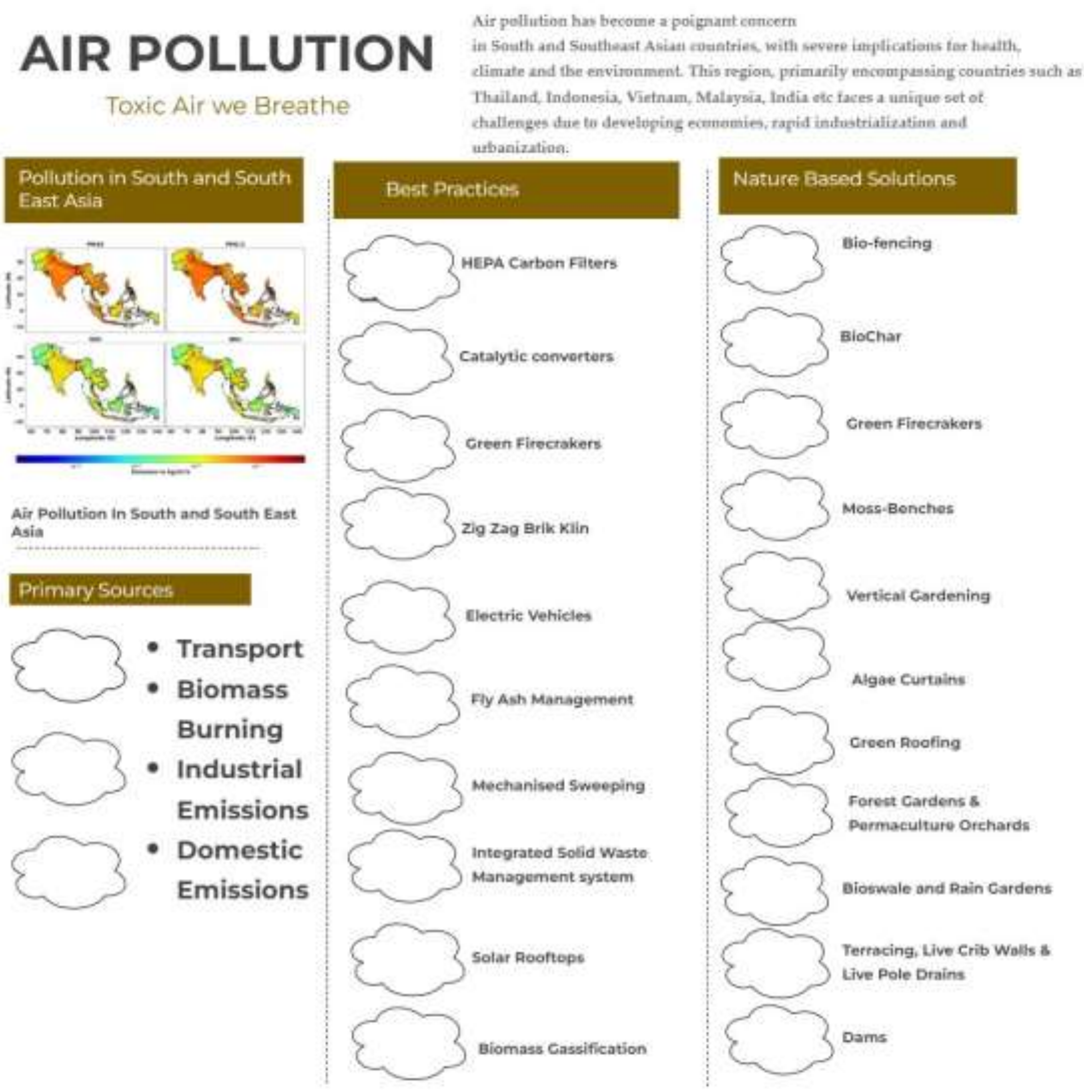
Chapter 1
Introduction



Air pollution is a global menace with overarching influences to human health, crop yield and environment. In the context of the South-East Asian region, the challenge of air pollution is particularly pronounced due to a combination of factors such as population explosion, industrial growth, uncontrolled vehicular emissions, fast expanding cities with rapid unplanned urbanization, and multifarious emission sources including biomass burning. This cocktail of challenges necessitates well planned mitigation frameworks for providing healthy living conditions for a metamorphosing population. This document aims to present a comprehensive action plan on mitigation strategies that can be employed to address the challenges posed by air pollution in the South and South-East Asian region. It will further provide a framework to make informed and pragmatic policy changes to implement viable practices for mitigation of air pollution.

The fundamental prerequisite for the effective and efficient management of air quality rests upon comprehending the knowledge and implementation gaps that have persisted thus far. This article endeavours to disseminate insights regarding the effectiveness and progression of air quality management protocols in India and other South and South-East Asian countries by consolidating data/reports from previous studies. A plethora of research has been conducted regarding the origins of air pollution in these geographical areas (https://aaqr.org/articles/special-issues/ssea). Substantial work has also been carried out by policymakers and scientists to adopt strategies to mitigate Air Pollution in the Indian context. Pioneering work has been done by several groups towards analysing the Policy implications and their impacts e.g. Gulia et al. (2021). A general shortcoming is that mostly the areas with extremely poor AQI bag the attention while masking the studies on causative factors hindering a scalable implementation strategy. A particularly neglected aspect across various air quality domains is also the socioeconomic repercussions of air pollution. While the health and disease burden are estimated regularly in recent times, the economic burden is often neglected which is an extremely important aspect of the discussion e.g. Pandey et al. (2023). The present document aims to assess the gaps in air quality mitigation research and policies, and aspires to produce the best practices based on effectiveness, appropriateness, and scalability on a larger magnitude.

The concept of nature-based mitigation strategies is also explored with respect to South and South Asian context. Nature based solutions (NBS) is a relatively new concept that is coming up in a big way as NBS are generally sustainable, have reduced negative footprints, lower economic burden and are viable in implementation by a diverse demography. As humankind has already stressed nature to its limits, solutions that are aligned with the principles of nature are likely to be more sustainable, affordable, implementable and successful. Recognizing the urgent necessity to confront air pollution in the South and South-East Asian region in a sustainable manner, this document systematically examines a spectrum of mitigation strategies, encompassing both conventional and nature-based methodologies. By scrutinizing the feasibility and adaptability of these approaches within a region's distinctive context, this document furnishes a roadmap for the effective implementation of measures aimed at combating air pollution on a larger scale.

Context

The South-East Asian region is notable for its densely populated urban hubs rapidly encroaching into adjacent rural settlements with agricultural fields. The escalation of air pollution within these locales imposes a substantial burden of health ramifications, encompassing ailments spanning from respiratory disorders to cardiovascular maladies. A nuanced understanding of situation based mitigation pathways can empower authorities to distribute resources with heightened efficiency using appropriate technologies targeting diverse areas requiring pollution abatement. Further, as the economic toll stemming from air pollution is significant, encompassing expenditures related to healthcare, diminished labour output, and degradation of infrastructure; dispensing insights into efficacious mitigation strategies actively contributes to the mitigation of the economic strain correlated with air pollution. Addressing air pollution mandates a comprehensive approach, which encompasses not only executing mitigation strategies but also fostering infrastructural advancements that endorse cleaner energy sources and sustainable transportation methods. This document will function as a catalyst, spurring the harmonization of endeavours pertaining to infrastructural enhancements with the overarching objective of ameliorating air quality. Under the GIZ TUEWAS innovation fund, the Air Pollution mitigation in South and South-East Asia (APM in SSEA) taskforce is planning for developing knowledge products (documentation of best practices and nature-based solutions for better air quality management). This would support the efforts made by various agencies to improve the air quality in the South and South-East Asian region.

Scope of the Project

This document will serve as a single point destination on solutions related to air pollution mitigation. Using detailed investigation of locally demonstrated success stories from a plethora of implemented practices, this document proposes a set of 10 best practices that are tested solutions for air quality improvement with scalability to the South and South-East Asian region. The document will also be a comprehensive compilation of available nature based solutions with focus on 10 such solutions that are likely to have easy acceptability among a diverse demography including citizens and authorities.

Objectives

The objectives of this report are as follows:

- Scoping of contents after interaction with stakeholders, desk research and GIZ taskforce members.
- Specifically, to do a deep dive to identify most available nature-based solutions for supporting air pollution mitigation in the region.
- Developing strategic document(s) for identifying 10 best practices (could be social, technological, science based etc.) in the South and Southeast Asian region.

Stakeholders

With respect to this report, the stakeholders consist of:

- Common citizens as the solutions are addressed to their problems.
- Municipal Authorities as they are at the end point of the implementation process.
- Government organisations and regulatory authorities like pollution control boards as they form a vital bridge between top-level policy-makers and bottom level implementing taskforces.
- Bureaucrats and policy makers who carry the power of decision making.
- Researchers, whose inputs influence the decisions of policy-makers.
- Various NGOs and organizations working in allied fields

Organisation of report

This report will consist of five Chapters. A comprehensive introduction to the topic is provided in Chapter 1, including context, scope and objectives of the proposed documentation. The methodology to be adopted for this work is discussed in Chapter 2 including the development of project framework, timelines and approach. Chapter 3 will be a comprehensive report on best practices aimed at mitigating air pollution at national as well as international levels and elucidates key learning from the tested best practices, including details of technology, viability, socioeconomic effects and potential to reduce air pollution from different identified sources. Chapter 4 provides a list of available nature-based solutions across different countries of the world for improving air quality that is expected to have easy acceptability by the citizens and the authorities. Chapter 5 is the concluding chapter and summarises the key findings w.r.t. best practices as well as Nature based Solutions. It also includes the current gap analysis, co-benefits and way forward. Concluding remarks, way forward and references are also given at the end of each chapter.

Chapter 2
Methodology

A project implementation framework for project execution has been developed following the ToR and inputs received in inception and progress meetings with GIZ.

Development of Project Framework

The project framework is being developed keeping in mind the project objectives and the mutually agreed upon timelines as per ToR. The project will involve a compilation vast amount of information into a judicious categorisation of information related to 'Implementable Best Practices' and 'Viable Nature Based Solutions' to reduce air pollution. The first task will be compilation of the information using approach provided in the following subsection followed by shortlisting of information into a knowledge database of Best Practices and Nature based Solutions.

Timelines

Work packages	August 31, 2023	September 30, 2023	October 31, 2023
WPL1: Scoping			
WPL2: NBS			
WPL3: Best Practices			

milestone 1 **milestone 2** **milestone 3**

- **Kindly note that in the timelines tasks 2 and 3 are exchanged compared to the ToR.**

Approach

This report is based on inputs from various stakeholders as well as desk research. In addition, we will identify major sources of air pollution in South and South-East Asia. Henceforth, we will make a repository of relevant information which will be cursorily mentioned in this report. After that, I will shortlist 10 best practices and 10 nature based solutions from the available information and deep dive into them for details. The shortlisting will be based on the identified sources of emissions, viability of implementation, scalability to different environmental and geographical settings and acceptability among different social strata as well as the inputs received from the Project monitoring committee at GIZ.

Data/Information Collection

The data and information collection will be based on interaction with stakeholders which will point up important avenues worth diving into and subsequent literature review.

Literature review

Literature review will be passed on research papers, policy papers, documents and white papers, court judgements, as well as web-based material

While most of the report is based on Desk research, we have additionally taken inputs of experienced stakeholders from different sectors, whose insights have helped us to deduce the priority avenues for framing of this report.

Interaction with stakeholders

Telephonic

Sample MoM1

Date: 29 August, 2023
With: Dr. Anirban Middey (Official from NEERI)

Key learning:
NEERI is actively involved in development of technologies and suggesting appropriate policies

Policy interventions:
Ban of Normal crackers and permission for Green crackers developed by CSIR- NEERI

Technological Intervention:
Biofencing for fly ash suspension using bamboo plant based for suppression of dust from industries including co-benefits for workers involved in bamboo plantation

Best practices:
Electric Vehicles, Green crackers

Kowledge repository:
NCAP, CPCB

***Sample* MoM2**

Date: 30 August, 2023
With: Dr. Arvind Kumar Jha (Scientist E, Official from Central Pollution Control Board in Gujarat)

Key learning:
Upliftment of Land fill sites helps remove emissions from waste
CNG is a major affordable alternative to reduce vehicular emissions e.g. CNG buses and even CNG garbage collection vans
Fugitive waste
CPCB is improving the monitoring network in India Network with 300 continuous and 650 manual monitoring stations, surprise checks are being done to ensure ethical monitoring, incentive on improving number of good days.

Policy interventions:

NCAP is a significant policy advancement in India, 132 non-attainment cities based on aqi standards and million plus population, 6-7 ministries are involved, the AQI of Ahmedabad has improved from 185 to less than 100 breach days
15th finance committee for 2021-26: The total grants to local bodies will be Rs 4360 billion INR (83 INR = 1 USD).
Boost to Green energy and climate action will increase renewable energy by 40% in next 7 years decreasing dependency on fossil fuels
Industries being located to Outskirts of cities and beyond
Pollution status certificates for vehicles will now be accompanied by online surveillance to reduce foul pay in obtaining certificates
Vehicles with visible plumes to be confisticated.

Technological Intervention:
FAME India - Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India deploying electric vehicles in different cities
White surfacing of roads has been effective in reducing temperatures by 2 degrees
Metros
Multi level parking
Green Belts
Management of solid waste, medical waste and e-waste. The last one will also reduce the dependency on the illegal child labour in regions like Moradabad, India.

Best practices:
Electric Vehicles, White Surfacing of roads, Electrostatic Precipitators

Cobenefits:
Swarnim Chaturbhuj (Golden quadrilateral) plan to improve road network will reduce city intrusion of vehicular traffic and increase efficiency of goods transportation
Creation of parking spaces and multi-level parking to reduce traffic congestion in cities
Atal Mission for Rejuvenation and Urban Transformation (AMRUT) is a development mission launched by Prime Minister of India in June 2015 focussing on infrastructure establishment through urban revival projects to ensure adequate water supply and robust sewage networks for urban transformation
Swatch-Bharat Mission in conjunction with AMRUT for enhancing cleanliness and planning drives has multiple co-benefits like removal and processing of sewerage reduces related emissions at leakage points within cities, even drainage management and levelling of roads to prevent water logging reduces fugitive drainage emissions
Supply chain management and reduction of fugitive emissions

Kowledge repository:
NCAP, Air Quality Health Index

Sample MoM3
Date: 31 August, 2023
With: Neeraj Mathur (Chief Environmental Engineer, Official from Rajasthan State Pollution Control Board)

Key learning:
Discussed about the 5 non-attainment cities in Rajasthan: Alwar, Jaipur, Jodhpur, Kota, Udaipur and learnt that particulate pollution is actually increasing in Rajasthan

Policy interventions:
Action plans are in place for Critically Polluted Areas.
Comprehensive Environmental Pollution Index (CEPI) index is used to characterise environmental quality for a given location.

Technological Intervention:
Massive plantation drives

Sample MoM4
Date: 1 September, 2023
With: Dr. Anirban Middey (Senior Principal Scientist, NEERI, Kolkata)

Key learning:
NCAP, Green Firecrackers, Green Belt.

Policy interventions:
Supreme Court order to ban traditional firecrackers and promote Green Crackers formulated by NEERI. Green corridors including bamboo plantation to sustain employment needs.

Technological Intervention:
Green firecrackers

Sample MoM5
Date: 4 September, 2023
With: Dr. Mohan P. George (Former Senior Scientist and Retd. Addn. Director, Delhi Pollution Control Board, New Delhi)

Key learning:
Discussed at length regarding both ambient pollution as well as industrial pollution. He discussed about the combined role of meteorology and human activities on air pollution in Delhi and IGP region e.g. burning in Punjab at the onset of winter juxtaposing with increased indoor heating and cooking activities in villages. He also discussed the role of seasonal dust & Western Disturbances on air pollution in Delhi and IGP. He stressed on the control of dust as this is the major pollution causing ingredient in India. He said out of 134 non-attainment cities, only about 37 have some sort of source apportionment studies available. Further, most of the automatic pollution monitoring stations are in big cities or metros, so there is a disproportionate lack of data being collected at sources e.g. in crop burning regions.

Policy interventions:
Mechanised cleaning of Road along with use of water sprinklers.
NCAP

He also said that cleaning of roads near dividers and dumping of the waste nearby does not help and is brought back by meteorology if not treated. Also, burning of leaf falls on roads and parks does not help in curbing air pollution. Further, he discussed the need of creating infrastructure e.g. good roads, clear footpaths etc

Technological Intervention:
He discussed the concept of green city with community kitchens. Also, remote sensing is a good way to gauge vehicular details and pollutant concentrations.

Survey:
Sample countries: Japan, Rwanda, India, South Africa, Switzerland, Norway
Sample designations: Scientists, Implementing Authorities
Total responses: 7
Relevant questions from Questionnaire:

- What are the major causes of air pollution in your region/country (1-5 causes from given options)?
- Which of the following is more relevant for your area w.r.t. air pollution
  a. Local Emissions b. Transported Pollution c. Both
- What are the best practices adopted in your country to reduce air pollution (1-5)?
- Are you aware of any nature-based solutions (NBS) being implemented/ planned for improving air quality in your region/country?

Table 2.1: Stakeholder survey

Sl No	Name	Designation & Specialisation	Office	Best Practices in Country	Nature Based Solutions
1	Dr. Prabir Patra	*Senior Scientist,* IPCC lead author, Climate Change, Greenhouse gases,	Research Institute for Humanity and Nature (RIHN), **Japan**	Control **vehicle quality**, Strict emission control, Managed traffic usage	Application of biochar
2	Steven Higiro	*Public Weather Service Officer,* Climate Change Specialist	Rwanda Meteorology Agency**, Rwanda**	Trying to import **electrical cars** so to reduce air pollution	
3	Dr. Anirban Middey	*Principal Scientist,* Air Pollution	CSIR-NEERI, **India**	Control methods at Source of emissions	
4	Dr. Cheledi Tshehla	*Air Quality Researcher,* EOSP	GDARDE, **South Africa**	South Africa has air quality management legal frameworks that binds all spheres of government to develop and implement air quality management plans.	Planting trees and vegetation cover for mine tailings
5	Dr. Martin Steinbacher	*Senior Scientist,* GAW measurements	Empa, **Switzerland**	(for sulphur species): **desulphurization of fossil fuels, exhaust gas after treatment** (for VOCs): implementation of the **2-way catalyst** (for particles): **particle filters** promotion of public transport and restrictions of individual transport	
6	Sunny Kapoor	*Director, Mitsubishi UFJ Financial Group*	Bangalore, **India**	No inputs	Green Belt
7	Dr. Sourangsu	*Senior Researcher*,	Oslo, **Norway**	a. Subsidy on electric vehicles.	https://www.norde

	Chowdhury	CICERO Center for International Climate Research		b) Wide use of hydroelectric energy. c)A tax and refund scheme to collect and safely destroy HFCs and a tax system encouraging the use of climate-friendly alternatives d)emission reductions in other countries either through the EU Emission Trading Scheme	n.org/en/project/nature-based-solutions

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2. Pandey, D., Sharps, K., Simpson, D., et al., (2023) Assessing the costs of ozone pollution in India for wheat producers, consumers, and government food welfare policies. PNAS. 120 (32) e2207081120. 10.1073/pnas.2207081120

Chapter 3
Best Practice Document

In this chapter, we are going to list the best practices (to reduce air pollution) that are in use today and despite their origin at any part of the globe is now being implemented at least in one place of South/South-East Asia.

General Understanding

Air pollution has emerged as a significantly growing threat to public health, the environment, , and the ecosystems. The repercussions of air pollution to human health and agriculture are a heavily researched topic. Today's research is not only limited to air pollutions sources and its characterisation but also diverged to socio-economic aspects including co-benefits of reducing air pollution on human health, plants, productivity at workplace and the economy in general. Simultaneously, there has been planning as well as efforts at different level of governances including national, state and municipal levels as well as independent organisations including corporates and NGOs. In fact, air pollution mitigation efforts are also popular as Corporate Social Responsibilities (CSR) initiatives. However, despite the need and now honest intention at different levels, the efforts are not concerted due to lack of reliable best practice documents. The emission from different industrialization, urbanization, and transportation activities continue to eject harmful pollutants into the atmosphere at alarming levels. At this juncture, the need to look for effective strategies for combating air pollution mitigation has become imperative. The pursuit of best practices for mitigating air pollution is not only to delve into the existing technologies and their efficiency but is also a crucial dedication to the preservation of our atmosphere. This document is a comprehensive exploration of the essential principles and strategies that underpin the best practices for air pollution mitigation, highlighting their effectiveness, cost benefit analysis and success stories.

Source Identification

Air pollution has emerged as a poignant concern in South and South-East Asian countries, with severe implications for health, climate and environment. This region, primarily encompassing countries such as Thailand, Indonesia, Vietnam, and Malaysia, India etc faces a unique set of challenges due to developing economies, rapid industrialization and urbanization. To have an understanding regarding the best practices w.r.t. air pollution mitigation; we need to recognise the major sources causing air pollution. Tracing the sources of pollution is a critical step to address this concern effectively. The following is a summary encompassing a compilation of diverse research endeavours conducted to apportion the emissions in South and South Eastern region to different sources: However, this study requires regional analysis as the major local sources contributing to air pollution in a region due to varied socio-economic activities and lifestyle of local communities. Some of the major sources of air-pollution in South and South-East Asia are industrial emissions of CO, NOx, SO2, Hydrocarbons, particulate pollution from construction activities, road dust, mining and industrial activities, burning as well as natural emissions causing secondary pollution e.g. oxidation of gases into secondary particles. The following is a summary encompassing a compilation of diverse research endeavours conducted to apportion the emissions in South and South Eastern region to different sources: Going through various existing research articles, this section intends to provide an insight into the various contributors to air pollution in South and South-East Asian countries. Foraging through the research articles, it offers a comprehensive overview of the key sources of emissions and the measures suggested by the researchers to tackle them in the region.

Table 3.1: Key sources of air pollution in South and South-East Asia

Research Paper	Area of Research	Identified Sources	Key Takeaways/ Measures suggested
(Guttikunda et al, 2014)	India	• Road Dust and Construction • Industries • Transport • Domestic • Waste Burning	• Inclusion of smaller sized particulate matter(PM 1) in monitoring frameworks. • Cleaner Fuel Adoption • Solid waste management • Energy efficient Industries
(Istiqom & Marleni, 2020)	Indonesia	• Traffic emissions • Biomass burning • Dust Emission. • Forest and Peat fires(especially in the dry season)	• PM2.5 to be made the primary parameter. • Implementation of Euro 4 strategy
(Hoang et al, 2017)	Vietnam	• Transportation(Especially Internal Combustion Engines). • Motorcycles contributor of - CO, VOCs, and HC emissions, • Trucks contribute to SOx and NOx. • Industrial Production	• Promotion of ethanol and Gasoline blends like (E5). • Exhaust gas recirculation systems (EGR) • EIA and other legislative actions. • Public Awareness
C40 Cities, 2020 [Tackling Air Pollution in Bangkok - C40 Cities]	Thailand	• Transport • Industry • Open Burning	• Short term : Sprinkling water, controlling construction and vehicular dust, traffic congestion management etc. • Long term : Improved Multi Module Public transport system, increased green spaces, emission standards for automobiles.
(Afroz, 2003)	Malaysia	• Open Burning • Transportation	• Stricter Vehicle emission standards.

		• Forest Fires	• Strict industrial emission standards • Public awareness on open burning.
(Velasco & Roth, 2012)	Singapore	• Industrial sector(Chemical, electronic, and metallurgic industries) • Petroleum and Gas • Shipping emissions • Transboundary episodic smoke haze events.	• Traffic regulations like Electronic Road Pricing and Vehicle Quota System to be more robust. • Inclusion of VOCs in monitoring list. • Improved Spatial and Temporal resolution of monitoring devices. • Multi- pollutant mitigation approaches.

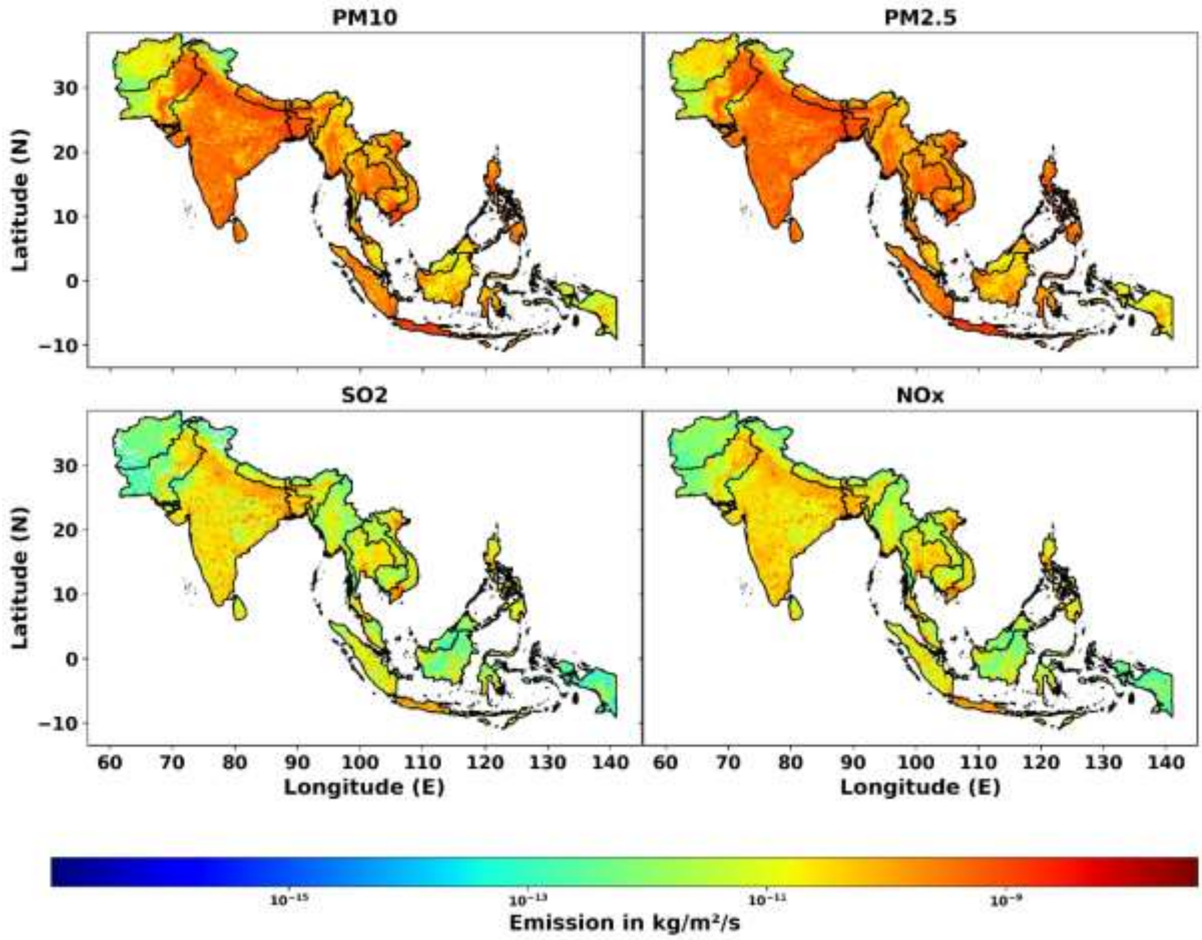

Figure 3.1: Overview of major air pollutants in South & South-East Asia. In South Asia, high emissions are distributed throughout northern India, Nepal, the southern point of India, and Bangladesh. In Southeast Asia, high emissions appear around some major cities including Bangkok, Hanoi, and Ho Chi Minh City, as well as Java. Indonesian emissions

seem to be on the same scale as the Indo Gangetic Plains (IGP) (*Source*: EDGAR Emission Database 2018).

Current Strategies

Post identification of sources, substantial work has been carried out by policymakers and scientists to adopt strategies to mitigate Air Pollution in the South and South Eastern context. The following table summarizes the different strategies in practices currently for mitigations

Table 3.2: Prevalent mitigation strategies for air pollution reduction in South and South-East Asia

Sl no	Method/Strategy/Policy/Regulation	Country	Features	Research on Impacts
1	Lower Sulphur content in Fuels like Diesel and petrol	India, Malaysia, Thailand	Reduces emissions of particulate matter and sulfur dioxide, which can cause respiratory problems and heart disease.	A study in India found that reducing the sulfur content of diesel fuel by 50% led to a 25% reduction in particulate matter emissions.
2	Catalytic Converters	India, Malaysia, Thailand	Reduce emissions of carbon monoxide, hydrocarbons, and nitrogen oxides, which can cause respiratory problems, smog, and acid rain.	A study in Thailand found that catalytic converters reduced carbon monoxide emissions from vehicles by up to 90%.
3	Reduced Usage of BS stage IV vehicles	India	Bans the sale and registration of new BS stage IV vehicles, which are less efficient and emit more pollutants than BS stage VI vehicles.	A study by the Center for Science and Environment found that banning BS stage IV vehicles would lead to a 15% reduction in particulate matter emissions in India.
4	Promotion of Cleaner Fuels like CNG and Ethanol	India, Malaysia, Thailand	Promotes the use of cleaner fuels, such as compressed natural gas (CNG) and ethanol, which produce fewer emissions than gasoline and diesel.	A study by the Thai Ministry of Environment found that switching to CNG from gasoline reduced particulate matter emissions from vehicles by up

				to 90%.
5	Stringent Construction Dust control Laws	India, Thailand	Enacts and enforces laws to control construction dust, which is a major source of air pollution in urban areas.	A study by the Indian Institute of Technology, Kanpur found that implementing stringent construction dust control laws led to a 20% reduction in PM emissions.
6	Stringent Industrial Emission Laws	India, Malaysia, Thailand	Enacts and enforces industrial emission standards that limit the release of pollutants into the air.	A study by the World Bank found that implementing stringent industrial emission standards led to a 10% reduction in particulate matter emissions in Thailand.
7	Massive Afforestation	China, Thailand	Plants trees and other vegetation, which can help to absorb pollutants from the air and improve air quality.	A study by the Chinese Academy of Sciences found that planting trees led to a 15% reduction in particulate matter concentrations.
8	Reduction of Coal consumption	China, Indonesia	Reduces the use of coal, which is a major source of air pollution.	A study by the Center for Research on Energy and Environment, Tsinghua University found that reducing coal consumption by 50% would lead to a 25% reduction in particulate matter emissions in China.
9	Palm oil production emission control	Indonesia, Malaysia	Implements measures to reduce emissions from palm oil production, such as by using cleaner technologies and managing waste products more effectively.	A study by the Indonesian Ministry of Environment found that implementing palm oil production emission control measures led to a 10% reduction in particulate matter emissions.
10	Mass Transit System	Thailand,	Develops and promotes	A study by the

		Singapore	the use of mass transit systems, such as trains and buses, which can help to reduce traffic congestion and air pollution.	Bangkok Metropolitan Administration found that the Bangkok Skytrain system led to a 15% reduction in particulate matter emissions.
11	Strict regulation on construction dust and open burning	Vietnam	Enacts and enforces strict regulations on construction dust and open burning, which are major sources of air pollution in Vietnam.	A study by the World Bank found that implementing strict regulations on construction dust and open burning led to a 10% reduction in particulate matter emissions in Vietnam.
12	Combating forest and peatland fires.	Malaysia	Enacts and enforces laws to prevent and suppress forest and peatland fires, which are a major source of air pollution in Malaysia.	A study by the Malaysian Ministry of Environment found that combating forest and peatland fires led to a 15% reduction in particulate matter emissions.

Pioneering work has been done by Gulia, S., Goyal, P., Prakash, M. et al. in analyzing the Policy implications in Indian context.
Details studies are also available for Malayasia:
As a result of he directive from the Malaysian government to administer Euro 4M by 1.1.20, a new fuel standard of RON95 petrol was introduced by companies like Petronas, Caltex, Shell, Petron etc. The resulting reduction in subsidies on fuels other than RON95 e.g. the lower octane RON92 caused Ron95 to take over the market with enhanced price (The Central Bank of Malaysia, 2011). The new fuel reduced NOx emissions by 7.7% but produced higher emissions of CO (36.9%) and HC (20.3%) (Salleh et al., 2018). CO emissions due to reduced engine speed from the RON95 petrol is 10% lower than the RON97 petrol.

In addition, a major highlight has been the installation of smog towers in big metropolitan cities. However, their limited spatial impact and effectiveness in cleaning large volumes of polluted air vis a vis the financial investment and maintenance has made them more of a white elephant rather than a workhorse. The smog tower installed at Delhi is currently lying defunct (Rs 22.9-crore smog tower at Delhi's Connaught Place lying defunct for past 7 months). The smog tower example highlights the importance of careful planning preceded by region specific scientific discussions before committing on huge investment projects like smog towers.

Kuala Lumpur City Hall (KLCH) as a part of the C40 Cities Climate Leadership. has paved the development of more intensive, practical, and integrated acts, policies, and strategies by policymakers and stakeholders in Malaysia. National policies in place include the national target of 40% emissions intensity reduction, National Energy Efficiency Plan, National Green Technology Policy, National Policy on Climate Change and Renewable Energy Act. A significant development worth mentioning is the Kuala Lumpur Low Carbon Society Blueprint 2030 committed to reduce emissions by 70% by 2022 against 2015 levels (Ho et al., 2018). This amounts to a decrease in cumulative emissions of 134,345 tCO2e and a financial saving in energy cost of RM76.1 million over this period of time. It has also committed to a target of 45% carbon intensity reduction by 2030 (relative to 2005 levels) (Kuala Lumpur City Hall, 2017; Shafie & Mahmud, 2020).

Policy Regulations

Policies and regulations to address air pollution vary from one country to another depending upon the political will, industrialization stage, urbanization, and economic prosperity. Despite this, various counties in South and South-East Asia have made efforts to regulate air pollution and adopted approaches to mitigate them. Below are a few such initiatives that have been outlined:

Table 3.3: Major policy frameworks for air pollution reduction in South and South-East Asia

Country	Period	Policy/Regulation	Pollutants
India	2019	National Clean Air Programme	PM2.5, PM10
China	2013	Action Plan for Air Pollution Prevention and Control	PM2.5
Thailand	2020	Thailand Clean Air Act Thailand Pollution Control Act	All pollutants
Philippines	1999	Clean Air Act	All pollutants
ASEAN countries	2003-2020	ASEAN Agreement on Transboundary Haze Pollution (AATHP)	PM, Haze
Malayasia	2015-2022	The Kuala Lumpur Low Carbon Society Blueprint 2030, improving petrol quality	CO2, PM, CO, NOx

Monitoring Framework

Air pollution is one of the major environmental concerns in South and Southeast Asia, with significant impacts on human health and the environment. To address this, a robust monitoring framework needs to be in place. Air quality monitoring networks essentially should measure key air pollutants, such as particulate matter (PM), ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2), with relevant temporal and spatial resolutions.

Inventories help us identify the major sources of air pollution in the region, including vehicles, industry, agriculture, and biomass burning. They also quantify the emissions helping in source apportionment and Air quality modelling. Air Quality Modelling can be used to simulate air pollution levels to monitor and predict the different future scenarios.

Countries in the region should facilitate air quality data sharing and collaboration on research and monitoring efforts. This improves the understanding of air pollution in the region and to develop more effective mitigation strategies. By implementing a comprehensive air pollution monitoring framework a significant progress can be made in reducing air pollution and improving air quality.

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10 selected best practices

BP1 : HEPA Activated Carbon Filters

Air pollution can be 5 times stronger in indoor air compared to outdoors. Sources of indoor air pollutants can arise from kitchen (VOCs from cleansers, gas stoves), bathroom (mold, odors microbial pathogens), laundry room (VOCs from cleaning products and solvents), Bedroom (perfume, hairspray, nail polish, furniture, carpet), living room (dust, smoke, paint,pet dander), subways (metros, cars, trains), factory settings, and offices. Removal of these gasses to prevent direct exposure of persons to toxic levels of pollutants employs several technologies including catalysts (https://catalysts.basf.com/industries/air-quality/indoor-air-quality) as well as HEPA activated carbon filters.

Details of technology

HEPA activated carbon filters are a combined filtration technology that integrates High-Efficiency Particulate Air (HEPA) filtration with activated carbon adsorption. HEPA filters are highly efficient at removing particulate matter, capturing particles as small as 0.3 micrometers on the other hand activated carbon filters, excel at adsorbing gaseous contaminants, and volatile organic compounds (VOCs) making them a great air quality enhancer. A summary of cross-section of studies from Indian metros on health impact of indoor air pollution is to be found at Vijayan et al., (2015).

Origin

The Second Battle of Ypres during the First World was the 1st time German troops used gasses as war arsenals. From masks of cotton pads soaked in urine to rags dampened with a sodium-bicarbonate solution, No approach went unattempted. German soldiers were discovered to have papers of special kind inserted between their masks for protection.This started a chain of developments of filters mostly for military use. Which initially started as an endeavor to design masks took turns to purify radioactive airborne particles mainly from the classified “Manhattan Project”. It was further developed to what we today know as HEPA filters by the US Army Chemical Corps and National Defense Research Committee.

While on the other hand, activated carbon filtration has been used for centuries. Almost all ancient civilizations have evidence of use of activated carbon for its adsorption properties. When these technologies are combined they come up with better technology for better air pollution mitigation.

Working

The ISO 16890 [35] classifies the filters used in general ventilation in four groups, based on the filter efficiency for a particle size: coarse, ePM10, ePM2.5 and ePM1. To belong to each category, a filter must be capable of capturing at least 50% of the particles in that size range (https://www.mdpi.com/2076-3298/9/9/118). HEPA filters provide single-pass efficiency of the filter media ≥99.75% if the filter is classified as H13 and ≥99.97% for filters classified as H14. These filtration characteristics are set according to the efficiency of the 0.3 μm particles, which is the most penetrating particle size (MMPS).

HEPA filters are designed to remove particulate matter from the air. They are highly efficient at trapping particles such as dust, pollen etc. It is even proved to be efficient in trapping certain bacteria and viruses. HEPA filters primarily use mechanical filtration techniques in which air forced through a dense network of fine fibers is made of materials like fiberglass or other synthetic materials where particulate matter is filtered. They capture particles as small as 0.15 micrometers with an efficiency of at least 99.97% (Liu et al., 2021).

Activated carbon filters on the other hand are specifically designed to remove gasses, odors, and volatile organic compounds (VOCs) from the air. They work through a process called adsorption. Adsorption is a process in which molecules or ions from a fluid (usually a gas or a liquid) stick to the surface of another host material. Unlike absorption, where substances are taken inside to fill the gaps within the bulk of a material, adsorption involves molecules adhering to the surface of the adsorbent material. This adhesion occurs due to various intermolecular forces, such as van der Waals forces, electrostatic interactions, and chemical bonding. Airborne gaseous chemicals (specifically volatile organic compounds, or VOCs) stick to the surface of carbon molecules until the surface is fully covered. The activation process is required to increase the surface area to enhance the adsorption through treatment by oxygen to open up pores of carbon atoms (https://www.pranaair.com/blog/functions-of-activated-carbon-filter/).This porous structure allows the activated carbon to adsorb (not absorb) gasses and odorous molecules. Once an activated carbon bed is saturated, the filter can no longer trap pollutants. In fact, chemicals with a greater affinity for an adsorption site can displace those with lesser affinity. However it should be noted that activated carbon is not effective at trapping solid particles like dust or allergens. It is effective primarily to gaseous pollutants and odors.

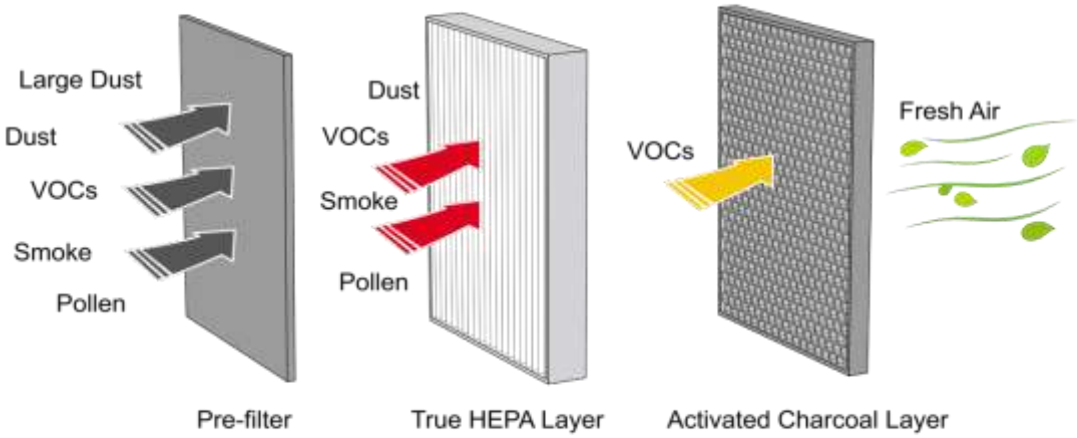

Figure 3.2: HEPA filter schematic (source: https://www.pranaair.com/blog/what-is-a-hepa-filter/)

HEPA (High Efficiency Particulate Air) filters and activated carbon filters are two distinct types of air filters that serve different purposes in air purification. However, they are sometimes combined into a single filter unit to provide comprehensive air cleaning. The HEPA filter captures particles while the activated carbon filter adsorbs gasses and odors. This combination provides a more thorough air purification solution.

When used together, these filters can effectively improve indoor air quality by removing a wide range of contaminants, including dust, allergens, smoke, pet odors, cooking odors, and chemical fumes.Control technologies by loading fibrous filters with activated carbon powder are being developed as a single-stage technology for the simultaneous removal of VOCs and particles from the gas stream. The efficiency of the carbon loaded filter was about twice as high as the efficiency of the clean filter with respect to the removal of particles with additional capability of purifying VOC in concentrated air streams over quite substantial time periods through interception, impact and diffusion (Agranovski et al., 2005).

Results

Best practices (national and international) and case examples

HEPA activated carbon filters are commonly used in air purifiers and HVAC systems to improve the air quality. These filters can effectively reduce various indoor air pollutants like particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs) and aromatics. The impact of these filters on reducing pollution is significant at places where high levels of indoor and outdoor air pollution are persistent. Different countries have reported varied responses to the use of these filters. Some of these are enlisted below.

Table 3.4: HEFA activated carbon filters implementation

Country	Impacts	Source
China	China has been grappling with severe air pollution issues, particularly in cities like Beijing and Shanghai. Studies have shown that the use of air purifiers with HEPA and activated carbon filters has led to improvements in indoor air quality in China, reducing exposure to fine particulate matter (PM2.5) and volatile organic compounds (VOCs).	(Li, 2017)
USA	Activated charcoal filters in vehicle cabin air filters can help reduce exposure to air pollutants while driving. A study published in Environmental Science and Pollution Research found that activated carbon filters in car air conditioning systems effectively reduced in-cabin concentrations of volatile organic compounds (VOCs) and particulate matter (PM)	US EPA 2023

South Korea	A study published in the International Journal of Environmental Research and Public Health found that the use of activated charcoal filters in air handling systems in subway stations in South Korea led to a reduction of up to 50% in levels of PM2.5, VOCs, and other pollutants. The study also found that the filters were more effective at removing pollutants during the summer months, when the air conditioning systems were in operation.	(Kim et al., 2019, 2020)

Key learnings

HEPA activated carbon filters play a crucial role in reducing indoor air pollution in various countries. Their effectiveness depends on several factors, including filter quality, usage, and the local pollution context. While these filters can significantly improve air quality and complement filtration with broader pollution control measures for a comprehensive reduction in pollution levels.

Impacts

Air pollution reduction potential for a particular source

The impact of HEPA activated carbon filters have been studied extensively and found to be positive. While electrostatic and plasma based technologies have poor efficiency and harmful by-products, activated carbon filters are comparably safer and emerge as a winner in air purification systems.

Table 3.5: Air pollution reduction potential of air pollutants

Pollutant	Impact	Source
PM 10	34 %	(Rawat & Kumar, 2023)
PM 2.5	57 %	(Rawat & Kumar, 2023)
Black Carbon (BC)	97 %	(Rawat & Kumar, 2023)
PM 1	70 %	(Rawat & Kumar, 2023)

Table 3.6: Minimum Efficiency Reporting Values (MERVs) of filters. Minimum Efficiency Reporting Values, or MERVs, report a filter's ability to capture larger particles between 0.3 and 10 µm (US EPA).

MERV Rating	Average Particle Size (µm)	Efficiency in Microns
1-4	3.0 - 10.0	less than 20%

6	3.0 - 10.0	49.9%
8	3.0 - 10.0	84.9%
10	1.0 - 3.0 3.0 - 10.0	50%- 64.9%, 85% or greater
12	1.0 - 3.0 3.0 - 10.0	80% - 89.9%, 90% or greater
14	0.3 - 1.0 1.0 - 3.0	75% - 84%, 90% or greater
16	0.3 - 1.0	75% or greater

Socio- economic effects

Among the most noble air pollution solutions related startups, SmartAir, founded by Thomas Talhelm, was launched in Delhi in 2015 and grown leaps and bounds, was based on circulating air through a HEPA filter (https://yourstory.com/2019/12/startups-fighting-air-pollution-india). During the pandemic, Smart Air provided over $70,000 worth of air purifiers to schools and hospitals around the world. Further, for every 1 USD invested in 2021, SMART AIR delivered 4.59 USD in Social Value. The Social Return on Investment (SROI) computation is available at (https://smartairfilters.com/wordpress/wp-content/uploads/2022/11/Final-Smart-Air-Impact-Report-1-2_compressed.pdf).

Implementation

HEPA activated carbon filters are being used in both industrial as well as business setups. They have the potential to reduce air pollution at the source itself thus reducing the overall burden of commercial and industrial emissions on the environment in addition to purifying indoor air keeping residents safe and healthy. It is recommended to scale up the use of HEPA filters in office, industrial and residential spaces apart from installing HEFA enabled purifying systems near both stationary and non-stationary polluting sources. One major advantage is that they do not need additional energy and infrastructure to be installed and operate.These filters can operate normally as part of a central heating and ventilation system, or part of air purification equipment, usually portable. In the first case, the filters act by filtering outdoor air, although they can filter indoor air if there is recirculation, and in the second case, the Portable Air Cleaners (PAC) exclusively purify indoor air, without air renovation (Mata et al., 2022).

Research by the EPA has shown that the concentration of an airborne particle as a function of time, C(t), that is being decontaminated by an air purifier can be calculated as follows (Kogan et al., 2008):

$$C(t)=C_0e^{-(CADR/V)t}$$

where CADR reflects the clean air delivery rate for the particular particle size and V indicates the volume of the room where the air purifier is placed. Moreover, the Air Changes per hour (ACH) attributable to an air purifier could be calculated as follows:

$$ACH=(CADR/V)\times 60h^{-1}$$

The amount of time needed for an air purifier to decontaminate the concentration of an airborne particle by 99% (as used by the CDC to determine guideline room shutdown times) can be calculated as follows:

$$shutdowntime(min)=[-\ln(0.01)\times 60]/ACH.$$

Commercially available HEPA purifiers routinely have a smoke CADR of ≥200 ft3/min. For a clinic treatment room that is 1000 ft3 (10 × 10 × 10 ft), this could translate to 12 ACHs attributable to just the HEPA purifier, which by itself would allow a room shutdown time of 23 minutes. If added to a clinic room with an HVAC (heating, ventilation, and air conditioning) system that already provides 6 ACHs, such a HEPA purifier could shorten the room shutdown time after an AGP from 46 minutes (6 ACHs from the HVAC alone) to as low as 15 minutes (18 ACHs from the HVAC and HEPA purifier combined) (Liu et al., 2021).

Success stories

Portable air cleaners (PACs) accentuated with HEPA filters have been shown to capture ≥ 99.97% of most penetrating particles measuring 0.3 μm in aerodynamic diameter, the most penetrating particle size (ASHRAE, 2021). In a 15 × 15 × 8 ft (1800 ft3) room, a typical PAC with a CADR of 300 cfm provides clean air equivalent to 10 ACH in contrast to ventilation based ACH of 0.5-1.5 (Allen and Ibrahim, 2021).

Based on 11 experimental studies on the potential of portable air cleaners (PACs) in eliminating airborne SARS-CoV-2 apart from removing regular air borne pollutants like PM and VOCs, Liu et al. (2021) concluded that HEPA purifiers were able to significantly reduce airborne SARS-CoV-2-surrogate particles with an efficiency that was essentially independent of particle size and at the highest clean air delivery rate (CADR).

In a study to assess the efficacy of air-cleaners with respect to their capacity to capture particulate matter and airborne allergen particles over a 6-month period in indoor environment, HEPA filters could filter 70% of 0.3-μm particles and 95% of 1.0-μm particles (Heide et al., 1997).

HEPA air cleaners significantly reduced the indoor PM2.5 level (33.5 ± 10.3 vs. 17.2 ± 10.7 μg/m3, mean difference (MD) = −16.3 μg/m3, $p < 0.001$) and indoor/outdoor PM2.5% (76.3 ±

16.8 vs. 38.6 ± 19.8%, MD = −37.7%, $p < 0.001$) evinced in a study conducted by scientists in Taiwan (Chen et al., 2022).

Vehicle carbon air electrostatic filters were found to provide 20–60% better filtration efficiencies (FE) across all particle diameters (6–520 nm) as well as for BTEX compounds (Chan et al., 2021). For 6 nm particles, FE from 78 to 94% were observed (from the worst to the best filters), while at 520 nm, FE varied from 35 to 60%.

Using a single-blinded randomized cross-over interventional study between November 2020 and May 2021 in the homes of adults who tested positive for COVID-19 in 29 homes, the overall mean PM2.5 and PM10 concentrations reduction achieved was 78.8% and 63.9% (n = 23), respectively (Lu et al., 2023).

Over four thousand portable air cleaners (PACs) with high-efficiency particulate air (HEPA) filters were distributed by The Public Health - Seattle & King County distributed over 4000 PACs with HEPA to homeless shelters during the COVID-19 pandemic and it was observed that a mere ten percent increase in total time use of these PACs significantly reduced indoor/outdoor total optical particle number concentration (I/OOPNC) by 0.252 [95 % CI: 0.150, 0.328; $p < 0.001$] (Huang et al., 2023).

Pros and Cons /viability

Pros	Cons
Health benefits for individuals with allergies or respiratory conditions.	Regular maintenance and replacement of filter components can be necessary.
Odor control and improved comfort.	Initial costs for high-quality HEPA activated carbon filtration systems can be relatively high.
Versatile application in homes, offices, healthcare facilities, and industries.	Only applicable for indoor air, closed spaces and industrial settings but not ambient air.

Challenges & Cost-benefit analysis

- Ensuring proper maintenance and timely replacement of filters to maintain effectiveness.
- Sizing and choosing the right filtration system for specific environments. - Addressing specific pollutants not effectively removed by this technology (e.g., some chemicals or ultrafine particles).
-The HEPA filter costs vary between INR 5000 to 35000 for home and office applications (https://www.gadgets360.com/home-appliances/hepa-air-purifiers) while for industrial

applications they may vary between few thousand INt to a few lakhs (https://dir.indiamart.com/impcat/industrial-air-cleaner.html).

Scalability and replicability

HEPA activated carbon filtration technology can be scaled for various applications, from small residential air purifiers to large industrial HVAC systems. However they are not typically used for ambient air but can effectively reduce the input of emissions to ambient air when directly used at the source. Their effectiveness in outdoor settings is limited due to the volume of air in outdoor environments and the dispersed nature of outdoor pollutants. Hence it needs to be combined with more extensive solutions to address outdoor pollution. Some replication in outdoor air purification using similar setups have been attempted. These are known as smog towers consisting of multiple air purifiers whose basic ingredient comprises HEPA filters. There are debates regarding efficiency of smog towers to address the issue of outdoor air pollution. Some opinions have termed towers in Beijing and Delhi as a failure as they could not trap gaseous pollutants because HEPA is primarily effective against particles (https://inc42.com/resources/are-smog-towers-an-effective-solution-for-air-pollution/, https://en.wikipedia.org/wiki/Smog_tower). However, notable air quality improvement was observed in Xian by virtue of the largest smog tower (100 m) reducing smog from severe to moderate levels with 15% reduction in PM2.5 levels (https://www.scmp.com/news/china/society/article/2128355/china-builds-worlds-biggest-air-purifier-and-it-seems-be-working).

Figure 3.3: World's largest smog tower in Xian (Source: https://www.weforum.org/agenda/2018/02/china-has-built-the-world-s-largest-air-purifier-to-battle-smog/)

The experimental facility in Xian is a scaled-down version of a much bigger smog tower that China hopes to build in other cities in the future. A full-sized tower is planned to reach 500 metres high with a diameter of 200 metres, according to a patent application they filed in 2014 (https://www.intelligentliving.co/worlds-biggest-air-purifier/). The size of the greenhouses could cover nearly 30 square kilometres and the plant should be powerful enough to purify the air for a small-sized city.

Smog towers were also set up at Delhi but currently lying defunct (https://timesofindia.indiatimes.com/city/delhi/rs-22-9-crore-smog-tower-at-delhis-connaught-place-lying-defunct-for-past-7-months/articleshow/104566966.cms). The smog tower example at Connaught Place, set up with a budget of 22.9 Crore INR, highlights the importance of careful planning preceded by region specific scientific discussions before committing on huge investment projects. Smog towers may benefit by modifying available technologies like HEPA with activated carbon filters. The smog free tower technology which has been created by the Dutch innovator Daan Roosegaarde may further benefit in efficiency using regionally relevant technologies including HEPA activated carbon filters (https://www.studioroosegaarde.net/project/smog-free-project). Combination technologies including HEPA and HVAC may also prove beneficial for air pollution reduction in indoor and outdoor environments (Rawat and Kumar, 2022). Further modifications to HEPA technology may also prove beneficial e.g. new activated carbon filters using pollen showing significant in-car NO2 reduction by 87.4 % (Matthaios et al., 2023).

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BP2 : Catalytic Converters

Details of technology

A catalytic converter is a simple emission control device employing basic redox reactions to reduce the pollutants emitted from an internal combustion engine of an automobile. It converts around 98% of the harmful fumes produced by the engine of a car and other automobiles into less harmful gasses. Toxic by-products like nitrogen oxides, carbon monoxide, and hydrocarbons of fuel produced in an oxygen deficit environment are converted into less hazardous substances such as carbon dioxide, water vapor, and nitrogen gas by use of these converters.

Origin

Catalytic converters were first developed in the 1950s to address the growing problem of air pollution resulting from the combustion of gasoline and other fossil fuels in vehicles. The concept of catalytic reactions had been known for some time, but the practical application of catalytic converters in automobiles began to take shape during this period. Catalytic converters were first introduced in American production cars on a wide scale in 1975 due to EPA regulations on toxic emissions reductions mandated by USA Clean Air Act.

Working with pictures

Catalytic converters work through a chemical process called catalysis. They are typically installed in the exhaust systems of vehicles including motorcycles, cars, trucks, trains, where they help reduce harmful emissions by converting them into less harmful substances. They are of various types enlisted below:

1. Oxidation Catalyst: One type of catalytic converter uses an oxidation catalyst, typically made of platinum and/or palladium. It promotes the oxidation of carbon monoxide (CO) and unburned hydrocarbons (HC) in the exhaust gasses to produce carbon dioxide (CO_2) and water (H_2O).

2. Reduction Catalyst: Another type of catalytic converter includes a reduction catalyst, often containing rhodium. It helps reduce nitrogen oxides (NO_x) by facilitating the reaction of NO_x with carbon monoxide and unburned hydrocarbons to form nitrogen (N_2) and carbon dioxide.

3. Ceramic Substrate: Inside the catalytic converter, there is a ceramic or metallic substrate coated with the catalytic materials. The substrate provides a large surface area for the catalytic reactions to occur.

4. Temperature and Oxygen: Catalytic converters require a specific temperature range and the presence of oxygen to function efficiently. Oxygen from the exhaust gasses helps initiate and sustain the chemical reactions.

The last section of the converter in vehicles controls the fuel-injection system. This control system is aided by an oxygen sensor that monitors how much oxygen is in the exhaust stream, and in turn tells the engine computer to adjust the air-to-fuel ratio, keeping the catalytic converter running at the stoichiometric point and near 100% efficiency. Modern emission control catalysts utilize monolithic flow-through supports coated with high surface area inorganic oxides and, in most cases, precious metals; this refractory oxide layer is called the washcoat (https://dieselnet.com/tech/cat_mat.php). The high surface area provided by the washcoat needed for the dispersion of catalytic metals is essential for both the catalyst activity and its durability (stabilization). The wash coat layer can be made up Al_2O_3 (alumina): micro & nano, and yttria whereby maximum conversion of yttria dual can be attributed to the adhesion properties of the wash coat with the substrate (Jeyakumar et al., 2019). Other materials like SiO_2 (silica), TiO_2 (titania), CeO_2 (ceria), ZrO_2(zirconia), V_2O_5 (vanadia) are also used.

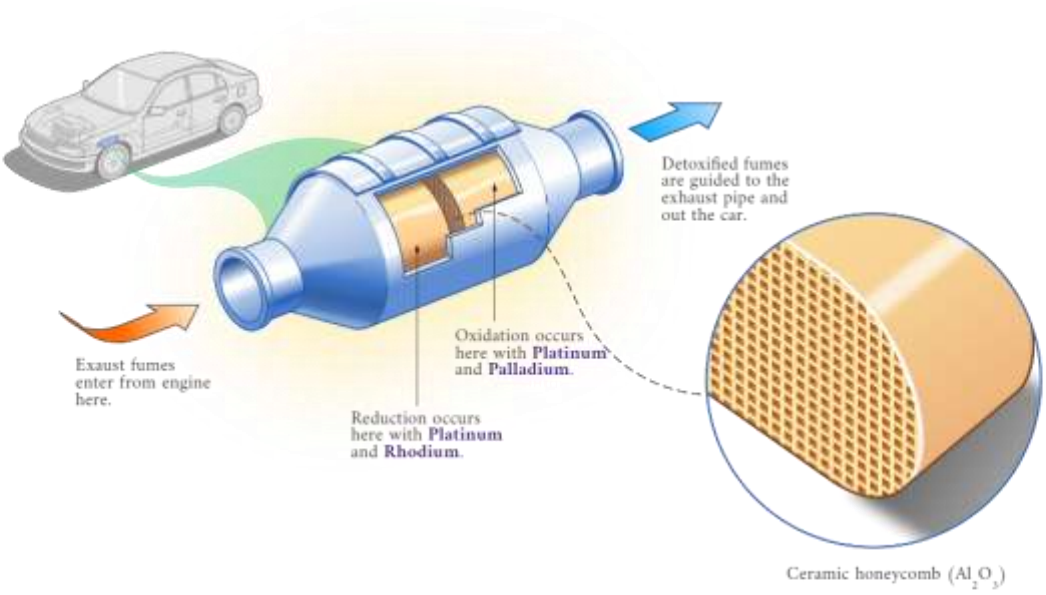

Figure 3.4: Basic Catalytic Converter. (CC BY 4.0; Ümit Kaya via LibreTexts)

Catalytic converters can effectively convert over 90% carbon monoxide (CO) and unburned hydrocarbons (HC) into less harmful carbon dioxide (CO2) and water (H2O) in gasoline vehicles while for diesel vehicles which additionally emit particulates, a particulate filter is used in conjunction with catalytic converters. While 2 way catalytic converters are based mainly on oxidation (of CO and hydrocarbons), 3 way catalytic converters additionally allow reduction of NOx into N2 and O2. This system utilizes one or more O2 sensors to oscillate the fuel mixture between lean and rich conditions, allowing for optimum reduction of all three emissions i.e. NOx, HCs and CO. Further, 4 way converters additionally target PM on the same support.
(https://www.walkerexhaust.com/support/tech-tips/evolution-of-the-catalytic-converter.html).

Results

Key learnings

About 35% of the CO, 30% of the HC, and 25% of the NOx that go into the air come from the transportation sector (Dey and Mehta, 2020). Governments of different countries have tried and are trying to control emissions in this sector. The internal combustion engine requires a mixture of fuels and air and its efficiency depends upon the air–fuel ratio. In the lean mixture conditions the vehicle produces less amount of CO and HC but more NOx gasses while in the rich mixture conditions the vehicle produces more CO and HC and less NOx gasses. Between petrol engine and diesel engines, the petrol engine produces more CO and HC but less NOx and particulate matter. The controlling techniques of exhaust gas emissions are engine modification, fuel pretreatment, fuel additives, exhaust gas recirculation (EGR) and catalytic converters. Among these, the catalytic converter has been effective and consistent for reducing the noxious tailpipe emissions so that it was developed for use in the trucks, buses, cars, motorcycles and other construction equipment. Luckily, the increase in air pollution due to increasing vehicular numbers has been accompanied by the evolution of catalytic converter technologies that not only bring a ray of hope in the dismal fight against air pollution but also bring in several co-benefits.

Impacts

Air pollution reduction potential for a particular source

Catalytic converters can effectively convert over 90% carbon monoxide (CO) and unburned hydrocarbons (HC) into less harmful CO2 and H2O. In a study in Indonesia for brass coated catalytic converters, Warju et al. (2021) found higher effectiveness with average reduction in CO and HC emissions at each RPM at 52%, and 29% respectively. To control the air pollution from vehicle exhausts in India, the Bharat stage emissions standards were formed to limit the emissions standards for major automobile exhaust pollutants such as CO, SOx, NOx, HC and PM from internal combustion engines. Petrol and diesel-powered two and three-wheelers, which constitute about 80% of the total number of vehicles, significantly account for on road pollution in cities in India, are targeted first in the 1989 through idle emission limits. Bharat Stage IV (BS-IV) , parallel to Euro IV regulations since 1 April, 2010 was applicable for various types of vehicles followed by stage 5 in 2017 and phase 6 in 2020 (Dey and Mehta, 2020).

Best practices and case examples

Case study on emission regulations from transport sector in Thailand based on Cheewaphongphan et al., 2020:

Transportation has been found to be a key component of economic growth and the second largest emitter of air pollution in Thailand contributing approximately 96% of greenhouse gas (GHG) emissions (Cheewaphongphan et al., 2020). Thailand has adopted regulations to control the quality of fuel and vehicle-engines based on the European standard (Euro) to control air pollution from vehicles since 1995 (Euro 1) for light-duty vehicles. The regulation has consistently adopted more intense control levels until reaching Euro 4 in 2011 and there is a plan to implement Euro 5/Euro 6 for light duty vehicles after 2023. The population in Thailand is expected to increase from 67 million people in 2015, peak at 71 million people in 2036 and decrease to 69 million people by 2050. The total passenger transport demand in Thailand is expected to increase from 591 billion pkm in 2015 to 769 billion pkm in 2050 with a peak around 2030.The transport demand by car is expected to increase from 209 billion pkm in 2015 to 392 billion pkm in 2050. Motorcycle transport demand is expected to increase from 122 billion pkm in 2015 to 141 billion pkm in 2050. The transport demand by bus is expected to increase to approximately 25 billion pkm in 2050, which is nearly double that of the base year 2015. Consequently, the total amount of fuel consumption is expected to increase from 10873 ktoe in 2015 to 14948 ktoe in 2050 with cars accounting for more than two-thirds of the total consumption, the rest is to be consumed by buses and motorcycles.The resultant amount of CO2 emissions in 2050 is expected to be approximately

44000 Gg, which is 1.4 times higher than the base year level. The regional trend of CO2 emissions has been found to have a correlation with the amount of fuel consumption. An upturn in CO emissions only by 0.5% per year seems to be caused by the impacts of transport demand growth compensating for the effects of the diffusion of vehicle-engine technologies in line with the current exhaust emission regulation levels at Euro 4 level for gasoline-cars and Euro 3 level for motorcycles. NOx emissions are primarily caused by vehicles with diesel engines, especially heavy-duty vehicles. The overall amount of NOx emissions is expected to be approximately 160 Gg in 2050, which is almost the same as that of the base year. The analysis presents the effects of implementing tighter regulations on exhaust emissions (TRE scenario) and as a result of the diffusion of Euro 5 or Euro 6 level vehicles, the amount of emissions will be reduced by 4%, 50%, 47%, 63%, and 63% for CO2, CO, NOx, PM10, and PM2.5 respectively.Advanced vehicles such as Euro 5 or Euro 6 can remove 93%, 50%, and 99% of air pollutant emissions for CO, NOx, and particulate matters.

Socio- economic effects

BASF, a leading developer of catalytic converter technology is now considering the markets in South East Asia which will bring additional job opportunities to this region directly and indirectly through subsequent recycling operations (https://catalysts.basf.com/news/basf-constructing-expanded-mobile-emissions-catalysts-manufacturing-facility-in-rayong-thailand).

Implementation

Improved Air Quality: Catalytic converters have contributed to cleaner air by reducing emissions of harmful pollutants, thereby reducing smog and improving public health.

Environmental Protection: They play a crucial role in mitigating the environmental impact of vehicle emissions, helping to protect ecosystems and reduce acid rain formation. In the 1950, it was invented by Eugene Houdry, a mechanical engineer Eugene Houdry to address the black smog that was choking Los Angeles and other American cities. Developed widely in the 1970s, these converters have been a boon to civilization allowing Governments to enforce emission regulations despite an overwhelming increase in the number of vehicles on roads (https://attheu.utah.edu/facultystaff/alumni-catalytic-converter/). Although catalytic converters are associated with a plethora of success stories, they are expensive due to scarcity of the precious metals e.g. platinum costs about $785 per ounce, apart from vehicular emission control, they offer multiple benefits and spin-off benefits. One of the leading companies, BASF Catalysts offers exceptional expertise in the development of technologies that protect the air we breathe & produce the fuels that power our world, associate their catalysts with a plethora of success stories (https://catalysts.basf.com/customers-success-stories):

- Using its proprietary catalyst, BASF has managed to save since 1998, at its own sites around the world and at customers' sites, nitrous oxide emissions that are equivalent, to about 20 million tons of CO2 per year.

- Deoxo® catalytic ozone converters for ozone removal systems for aircraft OEMs such as Airbus, Boeing, Gulfstream, Dassault, and other (https://aerospace.basf.com/deoxo.html)
- Oxidation-catalyst supplier to the power generation industry (https://catalysts.basf.com/industries/air-quality/stationary-emissions-control)
- N_2O decomposition catalysts adsorbs N_2O (laughing gas) and almost eliminates N_2O emissions. The decomposition of 1 metric ton of N_2O has the same effect as saving 298 metric tons of CO_2.
- BASF Catalysts Camet® oxidation catalyst systems destroy CO and VOCs from natural gas and oil fired turbines and boilers. BASF's CatCO™ CO oxidation catalyst technology may be applied for process streams with higher particulate content such as wood fired boilers.
- Rapid-cook technology and chain-driven charbroilers used in many fast food restaurants rely on high temperatures to cook meat quickly, but they also generate large amounts of smoke and odorous volatile organic compounds (VOCs), including formaldehyde and acetaldehyde. By some estimates, cooking four normal size hamburgers emits the same amount of VOCs as driving a current model car 1,000 miles. In addition to their impact on air quality, smoke and odors in restaurant kitchens can cause irritation and discomfort for employees. Therefore, emission control has become an important part of cooking-process design. BASF's food-service catalytic converters can reduce cooking emissions by more than 80%, reducing smoke and gases while meeting California's strict C-Cert requirements for VOC and smoke abatement. The systems are designed for easy installation and maintenance; running onexaust heat while being mounted on ventilation shrouds and ducts. In addition to its clean-air benefits, the technology also enables restaurant operators to lower operating costs by decreasing their gas usage and reducing the frequency of duct and roof cleaning. As a result, payback time can be less than a year.
- The proprietary zeolite based hydrocarbon trapping technology of BASF has proven effective in preventing hydrocarbon emissions leaking into the environment from cars from sources outside the exhaust system - such as the air intake system, fuel rail, exhaust gas recirculation system and the gas tank. This has helped carmakers to meet increasingly stringent California and federal standards for evaporative emissions. .) The new zeolite, which is coated onto a substrate for excellent adhesion, has a high capacity to trap hydrocarbons within its pores and channels reducing "cold- start" emissions (pollution that escapes a car in the first minute or so after ignition. This "hydrocarbon trap" is placed between a car's air cleaner and engine, where it can capture hydrocarbons that are escaping through the air intake. This position is optimal because the air intake system contributes as much as 50% of total evaporative emissions. The trap absorbs hydrocarbons that are emitted when the

engine is stopped. Once the car is started and driven, the trap releases the hydrocarbons into the engine where they are burned. In this way, the new hydrocarbon trap continually regenerates itself. The hydrocarbon trap is designed to remain effective for 150,000 miles, and is tamper-proof so it avoids the use of costly on-board diagnostics equipment.

- Worldwide, an estimated 25 million gasoline-operated, two-wheeled vehicles are manufactured annually. BASF catalysts have evolved to meet increasingly stringent emission limits for these vehicles over the years.

Success stories

Outlook for India's Emission Control Catalysis for Motorcycle demand:

The increasing production of motorcycles in India is the primary reason for driving the market need for emission control catalysts. Although sales decreased following outbreak of COVID-19, the emission control catalyst market is again recording a steady growth. The global market was valued at USD 42.9 billion in 2021 and projected to grow at CAGR of 6.9% for next 5 years. Same trend is expected for India (https://www.marketsandmarkets.com/Market-Reports/emission-control-catalyst-market-217359123.html). In fact, BASF has expanded its production capacity of mobile emissions catalysts in Chennai in 2021.

Following are some success stories attributed to BASF, one of the leading catalytic technology leaders (https://catalysts.basf.com/customers-success-stories)

- Over one thousand school buses across the United States were retrofitted with clean-air technology from BASF under the Environmental Protection Agency's (EPA) Clean Buses for Kids Program. Each year, American children spend three billion hours on school buses, 99% of which are diesel. BASF's technology was praised for its easy, cost-efficient installation and solid performance in reducing harmful emissions, including particulate matter, hydrocarbons and nitrogen oxides .
- The goal of the Big Dig Diesel Emissions Reduction Project was to reduce emissions near homes, hospitals, underground construction areas and fresh air intakes. The project included retrofitting construction equipment with diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs). BASF supplied diesel oxidation catalysts and BASF DPX™ diesel particulate filters for this project. According to contractor experience, the equipment retrofitted with catalysts did not suffer any loss of power or require any additional fuel or maintenance.The retrofitted equipment showed an approximate reduction of 36 tons/year for carbon monoxide, 12 tons per year of hydrocarbons, and 3 tons per year of particulate matter.
- Kowloon Motor Bus Company (KMB), Hong Kong's largest operator of public buses, undertook to retrofit one third of their vehicles with BASF's catalytic converter

mufflers, installing the technology on all 1,800 pre-1994 buses in their fleet. The catalytic converter mufflers on KMB's buses are preventing more than 3,000 metric tons of pollution from entering Hong Kong's air every year.

- Philadelphia buses: While diesel particulate filters have been proven effective in many retrofit programs, they traditionally require diesel fuel with very low sulfur levels. This presented a problem for Philadelphia, which only had access to 350 ppm sulfur diesel fuel for their buses. BASF DPX™ filters provided a solution to that problem. Currently over 400 of Philadelphia's buses have been retrofitted with BASF DPX™ filters, preventing more than 1000 tons of pollution from entering the city's air. Importantly, this program was one of the first of its kind funded by a CMAQ (Congestion Mitigation and Air Quality improvement) grant from the government.
- The evolution of emission control in motorcycles is similar to automobiles, notably the phasing in of increasingly-stringent regulations on hydrocarbons, carbon monoxide and nitrogen oxides using 3 way catalysts.
- Yuchai Machinery Corporation, the largest engine manufacturer in China has incorporated BASF's selective catalytic reduction (SCR) catalysts using a catalytically active component coated on a ceramic honeycomb into its fleet of 6.5-liter and 8.4-liter diesel engines enabling heavy-duty diesel trucks to comply with stringent Euro norms .., The catalyst promotes a chemical reaction that converts NOx into water and nitrogen when a reductant, such as AdBlue® urea is added. .
- Running a lawn mower for only an hour emits as much pollution as driving a car 50 to 60 miles. Swedish manufacturer Husqvarnas in partnership with BASF put "green" back into lawn and garden equipment though the catalytic muffler reducing hydrocarbon and NOx emissions in half while nearly eliminating odor and visible smoke, at a cost of less than $4.00 per unit.
- Beijing's air pollution levels challenges came into limelight during China's widely attended 2008 Summer Olympics, presented as the first "Green Olympics", , To address the situation, Beijing transport authorities replaced thousands of older diesel buses with buses that meet Euro IV emission standards before the 2008 Olympic Games. BASF Catalysts came into rescue equipping Beijing with more than 1,000 new mass transit buses with SCR (selective catalytic reduction) catalysts. The ultimate result was many more clean-running mass transit buses operating on the streets of Beijing.
- Volvo Smog eating cars: In 2000, the world's first "smog-eating" cars from Volvo Car Corporation of Sweden on their popular luxury sedan, the S80 hit the road equipped BASF's PremAir® ozone-destroying catalyst. Since that successful launch, PremAir has been applied to many other Volvo models. PremAir catalyst can be applied to heat-exchange surfaces like car radiators and air-conditioner condensers to destroy harmful ground-level ozone as it passes over these surfaces.

Pros and Cons /viability

<table>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>Significant reduction in harmful emissions.</td><td>Catalytic converters can be expensive to manufacture and replace.</td></tr>
<tr><td>Improved air quality and public health.</td><td rowspan="2">Limited Effectiveness at Low Temperatures: They are less efficient when the engine is cold, as they require a minimum operating temperature to function effectively.</td></tr>
<tr><td>Established and proven technology.</td></tr>
<tr><td>Mandatory in many regions, ensuring widespread adoption.</td><td rowspan="2">Precious Metal Use: The catalytic materials often include precious metals like platinum, palladium, and rhodium, which can be expensive and subject to supply constraints.</td></tr>
<tr><td>Catalysts can last for many years before replacement is needed.</td></tr>
</table>

In a study in India, it was found that the conversion efficiency of the catalytic converter decreases when the vehicle runs above 45,000 km (Sharma et al., 2015). Catalytic converters can add weight and reduce exhaust flow, which can impact a motorcycle's power output; hence if emission norms are not very strict or the engine is smaller, manufacturers may avoid adding a catalytic converter. Overheating can destroy the components found within the converter. Further, traditional catalytic converters for cars use ceramics which are sensitive to vibrations preventing use in other applications for example motorcycles. Instead motorcycles use converters made from stainless steel or other metals that can better withstand vibrations. These converters are brazed during assembly and the high exhaust temperature requires a Ni-based braze alloy (https://www.hoganas.com/en/Industries/automotive-transportation/get-inspired/catalytic-converters/) .

Challenges & Cost-benefit analysis

Catalytic converters today have three major problems: they are inefficient because a bulk of the catalyst material does not come in contact with the air it's supposed to clean, they are expensive as they contain precious metals, , and a limited working temperature range. There is therefore the need to develop separate materials to address the problems of cost, performance, and temperature stability such that before a car or a factory 'warms up,' they're not spewing pollution that isn't cleaned, (https://chemistry.harvard.edu/news/cooler-catalytic-converters-cleaner-air-all)

Development of alternative, lower-cost catalyst materials is underway. Further, the efficiency of Palladium is less at temperatures below 400 Deg C which was overcome by changing the substrate on which the metal is place e.g. using Zeolite (https://www.s-ge.com/en/article/news/20182-psi-motor?ct). Moreover, vitrification of Palladium was prevented by addition of sodium to the Zeolite surface.

Due to the presence of expensive metals, theft of catalytic converters occurs at an enormous proportion and poses challenges for the administration and local authorities. Addressing the issue of catalytic converter theft for the valuable metals they contain is an imminent and important concern. However, recovery and recycling of Platinum Group Metals (PGMs) through buyback of used catalytic converters is also a lucrative business that is ethical (https://www.siamcatrecycling.co.th/) in contrast to the catalytic converter theft market. Catalysts containing equivalent ratios of platinum and palladium are expected to be launched to improve the quality of catalytic converters.

Since catalytic converters can be easily contaminated by sulfur and lead, the use of these converters requires use of lower sulfur containing gasoline and diesel fuels and near elimination of lead. Although catalytic converters have been a breakthrough technology by itself and are continuously evolving to address newer challenges, the continued improvement in catalytic converter technology to reduce emissions further is a must.

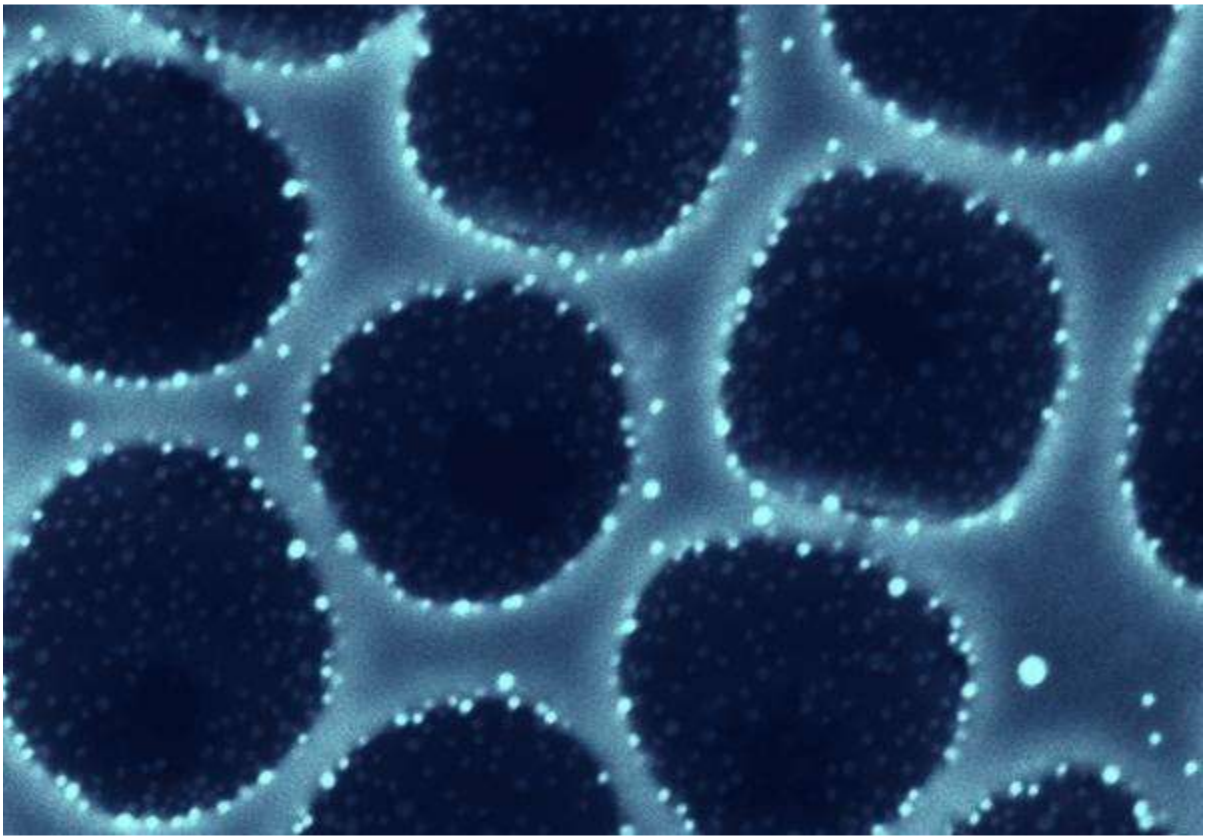

Figure 3.5 The butterfly-wing-inspired architecture allows precious metal catalysts (white) to be strategically placed on the porous scaffold (gray) so that the catalytic reaction is

much more efficient and cost-effective. *Credit: Wyss Institute at Harvard University (https://chemistry.harvard.edu/news/cooler-catalytic-converters-cleaner-air-all)*

Further, rising demand of battery operated electric vehicles is a major restraint to the growth of the catalytic converter market. However, for countries like India where EVs and plug-in hybrid EVs account for less than 1% of the market share, the catalytic converter market still has a major role to play. While the emission control catalyst market size was USD 41.9 billion in 2022, it is expected to be 77.5 billion USD in 2032. While mobile sources constituted 81% o this market in 2020, there are several emerging trends to sustain this market including advanced catalyst technology, increased use in the renewable energy sector and utilisation for environmental monitoring (https://www.globenewswire.com/news-release/2023/06/30/2697496/0/en/Emission-Control-Catalyst-Market-expected-to-increase-by-USD-77-5-Billion-by-2032-as-per-Acumen-Research-and-Consulting.html).

Scalability and replicability

Catalytic converters are scalable and have been widely adopted in the automotive industry. They are standard components in the exhaust systems of most gasoline-powered vehicles globally, and their application can be extended to other combustion sources, such as industrial processes. The automotive catalytic converter market is projected to grow at 7% with Europe as the largest market but Asia Pacific as the fastest growing market (https://www.mordorintelligence.com/industry-reports/automotive-catalytic-converter-market).

In summary, catalytic converters are critical components in reducing harmful emissions from vehicles, contributing to improved air quality and environmental protection. While they come with costs and challenges, they are a well-established and scalable technology with a proven track record in mitigating the impact of air pollution. Implementation of catalytic converters should be made mandatory in all kinds of vehicles including motorcycles. In addition, their use should be expanded beyond on-road vehicles to construction related vehicles, lawn mowers, biorefineries (Solarte-Toro et al., 2023), and so on. Catalytic converters are already an environmental success story (Taylor, 1987) but the story is yet to end.

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BP3 : Green Firecrackers

Details of technology

Firecrackers have traditionally been an important aspect of celebration. However the detrimental environmental impacts have compelled the researchers to look into sustainable alternatives that replicate the same level of grandeur with lesser pollution. Green crackers primarily try to replace the formulations and materials of the firecrackers to reduce emissions. To reduce the emissions, the sulphur and NOx content of the crackers are reduced to a minimal extent while sustainable materials are used for making them. In comparison to traditional firecrackers, green firecrackers also omit the use of harmful metals like aluminium, barium, lead or potassium.

Origin

CSIR-NEERI has been pioneering the research and development of green crackers since 2018 upon the directive of the honorable Supreme Court (https://www.neeri.res.in/img_homes/77301127_Definition_of_Green_crackers.pdf). A detailed analysis of the timeline of pollution abatement from firecrackers has been covered in CPCB status report 2017-18. The concerns came into prominence when the capital city of India, Delhi reported hazardous AQI levels. Visualize: Delhi's Air Pollution (2016-2021) – Smart Air. It developed new formulations for reduced light and sound emissions (SWAS, SAFAL, STAR) with up to 80% reduction in PM emission.

Working

CSIR NEERI categorizes green crackers into categories:

1. Improved firecrackers: Fireworks/firecrackers made with improved raw materials or replaced with sustainable materials (using different casings) such that there is a minimum of PM reduction of 30 % or more when compared with conventional composition of crackers/fireworks.
2. New formulation firecrackers: Fireworks/firecrackers having new and improved formulations (no sulfur content etc) to have at least a 30 % PM reduction when compared with conventional crackers/fireworks.

NEERI has developed several types of firecrackers namely :

SWAS: It releases water vapor to suppress dust, reducing particulate matter (30-35%), SO2, and NOx emissions. Its sound intensity is the same as that of conventional crackers.

STAR: This eliminates the use of KNO3 and Sulphur, leading to reduced PM (35-40%), SO2, and NOx emissions. It also has similar sound intensity as conventional firecrackers.

SAFAL: This minimizes the use of aluminum (only in flash powder), resulting in a significant reduction in particulate matter (35-40%) and maintaining sound intensity.

Figure 3.6: CSIR- NEERI 's improved Green firecrackers (source: [CSIR-NEERI's Light Emitting Crackers Category 1]())

Results

Best practices (national) as case examples

After the directive of the Supreme Court of India, green fire-crackers are starting to be manufactured on a wider scale in India. The hub of firecrackers at Sivakasi, which produces 90% of India's firecrackers has witnessed continuous waning of demand after ban on illegal crackers. Further, there has been a ban on barium nitrate, an oxidising agent used in pyrotechnics, has affected the making of firecrackers like phuljhari (sparkler), the rolling chakri (ground spinner), and anar (flowerpot) taking the sheen off the shine (https://www.business-standard.com/india-news/as-diwali-nears-what-s-taking-the-sheen-off-sivakasi-s-firecracker-sales-123102900320_1.html). However, it also prevents dangerous accidents apart from reducing the pollution on illegal crackers like the recent blasts in Kolkata firecracker factories (https://indianexpress.com/article/cities/kolkata/clusters-of-green-cracker-factories-to-be-set-up-in-districts-govt-forms-panel-8623639/). Further, the Calcutta high court has directed that no fireworks other than green crackers *bearing QR codes* would be imported and sold in West Bengal. This has also compelled the West Bengal govt. to set up new factories for manufacturing green crackers in the same places where the old setups exist which will also help people who are working in this sector for generations. This is a four way masterstroke as the people's employments are not robbed off, while the companies benefit from the traditional experience. At the same time the public benefits from abundant supply in the market vehicle Govt.benefits easy enforcement while keeping the people happy. Further, the Delhi Pollution Control Committee has been quite active to control nuisances of firecrackers and notified a complete ban on firecrackers in the national

Capital until January 1, 2023 last year. This ban included the manufacturing, storage, lighting, and sale of all types of firecrackers, including green firecrackers. To ensure that the ban is implemented in Delhi, around 285 teams, including officials from Delhi Police and the revenue department, are already in action. Recently, Deputy Commissioner of Gurugram. Haryana has banned sale, use of firecrackers, except green firecrackers during November 1, 2023 to January 31, 2024 (https://aninews.in/news/national/general-news/haryana-deputy-commissioner-bans-sale-use-of-firecrackers-except-green-firecrackers-in-gurugram20230928204149/). Additionally, e-commerce sites have also been taken into the loop not to sell firecrackers which are not green and conduct raids to implement the order and provisions made to take punitive action under relevant sections of Indian Penal Code Explosive Act 1884.

Key learning

Promoting green Firecrackers while simultaneously banning traditional/conventional crackers that emit harmful compounds like barium nitrate provides multiple benefits. These include

a. Reduction in gaseous air pollutants
b. At least 30% reduction of PM levels with or without suppresants
c. Reduction in toxic substances in the atmosphere
d. Reduction in ash content and size
e. Reduction in noise levels
f. Improved safety
g. New employment opportunities
h. Diving sustainable technology development
i. Curb on illegal fire cracker and explosive trade

Impacts

Air pollution reduction potential for a particular source

Table 3.7: Air pollution reduction potential for green crackers

Pollutant	Reduction	Source
Carbon Monoxide (CO)	Green crackers designed with cleaner combustion processes can significantly reduce carbon monoxide emissions, though specific reduction percentages may vary (Chakrabarty et al., 2020).	Chakrabarty, et al. (2020)
Particulate Matter (PM)	30-40% compared to traditional crackers	Ministry of Commerce and Industry, Government of India. (2022).

Nitrogen Oxides (NOx)	50-70% compared to conventional firecrackers (Mishra et al., 2019).	Mishra, et al. (2019)
Sulfur Dioxide (SO2)	80-90% compared to traditional firecrackers	Kumar et al. (2021).

Socio- economic effects

Green crackers have several socio- economic effects which include public health and safety of the workers. The reduction in air pollution levels, lower respiratory and other health impacts, and the support of local businesses make green crackers a promising solution for cleaner and more economically sustainable festive celebrations (https://www.neeri.res.in/img_homes/17530797_website_Photographs_Firecrackers.pdf).

Figure 3.7: Inspection of Final Product before demonstration at Sivakasi by CSIR-NEERI Team (Source: https://www.neeri.res.in/img_homes/17530797_website_Photographs_Firecrackers.pdf)

Implementation

A Supreme Court order in India has mandated a blanket ban on production of conventional firecrackers. It has been explained that green crackers don't contain aluminum, barium, potassium nitrate or carbon, making them eco-friendly. The manufacturing industries in India have to mandatorily follow the formula given by NEERI to be part of the legal trade on firecrackers. (https://www.thebetterindia.com/240791/diwali-2020-green-firecrackers-rules-pollution-purchase-tanfama-qr-codes-delhi-him16/). Several state governments in India have followed the supreme court's directive and banned the use of conventional firecrackers. (https://www.firstpost.com/india/what-are-green-crackers-and-what-makes-them-eco-friendly-and-less-polluting-10104851.html).

To guarantee the firecrackers complied with the norms, a series of technology-assisted steps have been introduced, e.g. every packet of firecracker will come with a NEERI logo printed on it (https://www.thebetterindia.com/240791/diwali-2020-green-firecrackers-rules-pollution-purchase-tanfama-qr-codes-delhi-him16/).

Success stories

Between 2019 and 2021, 785 industries have an understanding with CSIR-NEERI and registered for manufacture of green firecrackers (https://www.neeri.res.in/file_homes/46581446_Registration_05022021_firework.pdf). This is a successful juxtaposition of novel science with effective policy making in interest of the common citizen.

Pros and Cons /viability

Pros	Cons
Green crackers emit fewer pollutants,like sulfur dioxide (SO2) and nitrogen oxides (NOx), and particulate matter leading to improved air quality and reduced health risks.	Green crackers may be potentially more expensive for consumers in the short run. Though with more market penetration, this is expected to cease.
Green crackers also reduce the sound pollution and also maintain the aesthetics of traditional firecrackers.	Developing and perfecting green cracker technology still requires a lot more in research and development.
The lower emissions of harmful gasses and PM from green crackers contribute to a decrease in pollution-related respiratory problems.	Efforts need to be made for more adoption amongst the consumers accustomed to traditional firecrackers.
Government has introduced regulations and	Several complicated regulations from

incentives to promote green crackers.	government authorities and NEERI over formulations and non-disclosure agreements is a reason for discontent among several manufacturers.

Challenges & Cost-benefit analysis

The most challenging aspect of developing green crackers is to make them as visually appealing and culturally significant as traditional firecrackers. Apart from this, green crackers also face the challenge of awareness among the customers.

The newly developed green firecrackers are not only eco-friendly but are also 15-20% cheaper than traditional ones. This also impacts consumer acceptance and market penetration. (Ministry of Commerce and Industry, Government of India, 2022).

Even though the cost of production is high, the health care due to improved air quality is substantial. The local businesses create job opportunities and government supported research can drive innovation and economic growth (Department of Science and Technology, Government of India, 2022). The Sivakasi Firecracker hub had been in the forefront in adopting the green crackers. More than 10000 manufacturers have signed up for manufacturing green crackers with CSIR- NEERI. There also have been concerns about the shelf life of the crackers among the Firecracker traders, CSIR scientists have assured that if SOP is followed no such problem will arise. https://www.indiatoday.in/india/story/green-cracker-explainer-diwali-air-pollution-supreme-court-judgement-sivakasi-tamil-nadu-2285562-2022-10-15. Further, the stringent certification process handled by the Petroleum and Explosives Safety Organization (PESO) is a deterrent to many manufacturers.

Sivakasi, a city in South India has now become synonymous with the country's green firecracker industry with most of the manufacturers there having registering for CSIR-NEERI' approved concoctions , is now targeting the global market which is dominated by Chinese players. The size of Sivakasi's fireworks industry is approximately Rs 6,000 crore, and is poised for further growth due to its rapid adoption of environmental-friendly standards (https://www.moneycontrol.com/news/business/rs-6000-crore-sivakasi-fireworks-industry-eyes-china-dominated-global-market-9391581.html). Industry players based in the city with their 'green edge' are looking forward to making inroads in the global export market, where China holds the edge with an annual turnover of Rs 26,000 crore.

Scalability and replicability

Green crackers are both scalable and replicable due to their innovative, environmentally friendly approach to replicate the traditional fireworks. The government regulations supporting the manufacture and usage of green crackers makes it more replicable and easier for consumer penetration. Apart from this, NEERI's constant effort in improving the firecracker technology makes the process very robust. Further, the formula for green crackers suggested by the NEERI falls under a non-disclosure agreement, and only those manufacturers who have signed an agreement with the NEERI are permitted to manufacture the crackers.

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BP4 : Conversion of traditional brick kilns to zig-zag kilns

Details of technology

Traditional, brick kilns are normally observed to be highly polluting in nature. Hence, various research and development activities came up with modern technologies (firing pattern / technological advancements) like the Natural draught Zig Zag kilns, Forced Draught zig zag kilns, Hoffman Kilns etc.

Origin

The zigzag firing concept made its debut in the realm of kiln design with the Buhrer Kiln, a pioneering invention attributed to Jacob Buhrer of Switzerland in 1868. Buhrer's Kiln bore structural resemblance to the Hoffmann Kiln, but its hallmark innovation lay in the serpentine path along which air flowed. This zigzag configuration substantially increased the distance that air traversed within the kiln, fostering a turbulent environment essential for the firing process. To facilitate this airflow, a fan was ingeniously incorporated to induce the necessary draught.

Subsequently, the zigzag firing approach found widespread application in Habla Kilns, notably prominent in Germany during the interwar period between the first and second World Wars. These kilns also gained popularity in Australia. In the Indian subcontinent, the Zigzag Kiln made its entry through the pioneering efforts of the Central

Building Research Institute (CBRI) during the early 1970s. This innovation was subsequently adopted and replicated in Bangladesh and Nepal. These kilns were aptly named Induced/High Draught Zigzag Kilns, as they harnessed a fan to generate the draught required for efficient air circulation within the kiln. While sometimes this kiln without any external fan was also used with the zig zag firing pattern and named as Natural Draught Zig Zag kiln.

Buhrer Kiln patent details:

1. Title: Brick Kiln.; Inventor: Jacob Buhrer; Patent Number: US377511; Date of Patent: Feb 07, 1888
2. Title: Improved drying and burning Kiln.; Inventor: Jacob Buhrer; Patent Number: US82488; Date of Patent: Sep 29, 1868

Results

Best practices (national and international) and case examples

The devastating earthquake of 2015 in Nepal, left the people with bad memories with a huge destruction of life and property. However, amidst this chaos there were these brick kilns which were also destroyed within the valley. Once life started to go back to normal, it was essential to build back all that was lost. Now taking this as an opportunity, a few brick kiln owners, researchers, policy makers and others came together with a motto to build back better. Hence, the concept of Zig Zag kilns were introduced and championed by ICIMOD and associated organizations in the region. After quiet some efforts today all kilns with the Kathmandu valley have been converted into the zig-zag technology. Some studies conducted on the efficiency of these kilns suggest the followings.

Table 3.8: Average EFkgbrick (g/kg brick) with standard deviations

Kiln Type/Pollutant	SO2	PM2.5	BC
FCBTK	**1.2±1.2**	**0.2±0.1**	**0.03±0.01**
IDZK	**0.9±0.5**	**0.1±0.0**	**0.1±0.0**

Where FCBT represent traditional kiln and IDZK represent zig zag kiln

[Brick Kilns | Building Back Better - YouTube]

Working with pictures

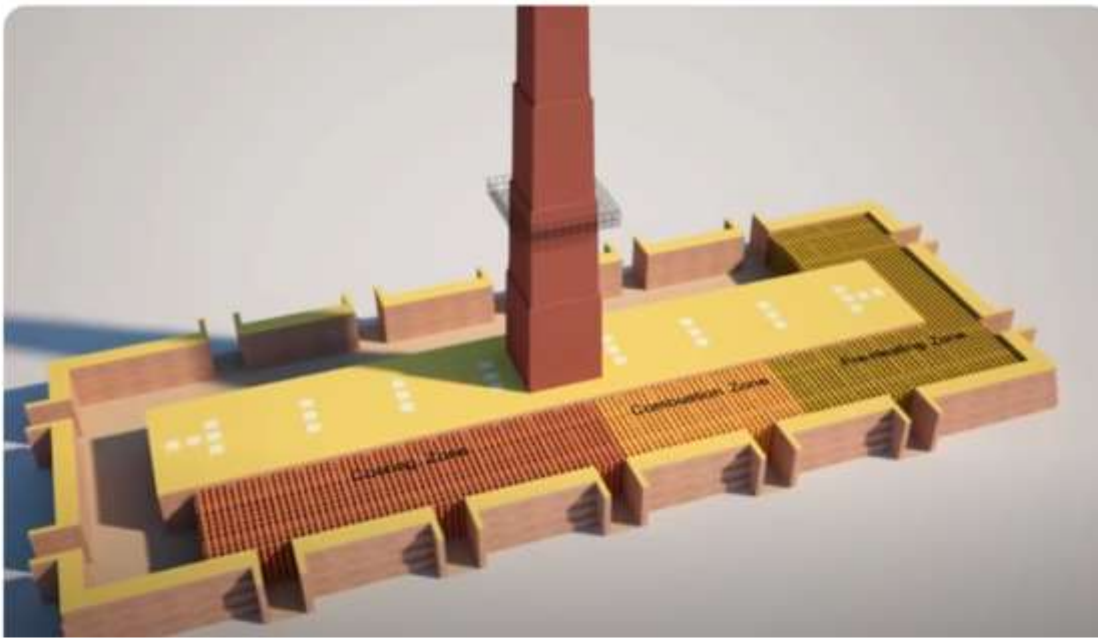

Figure 3.8: Brick kiln with different zones

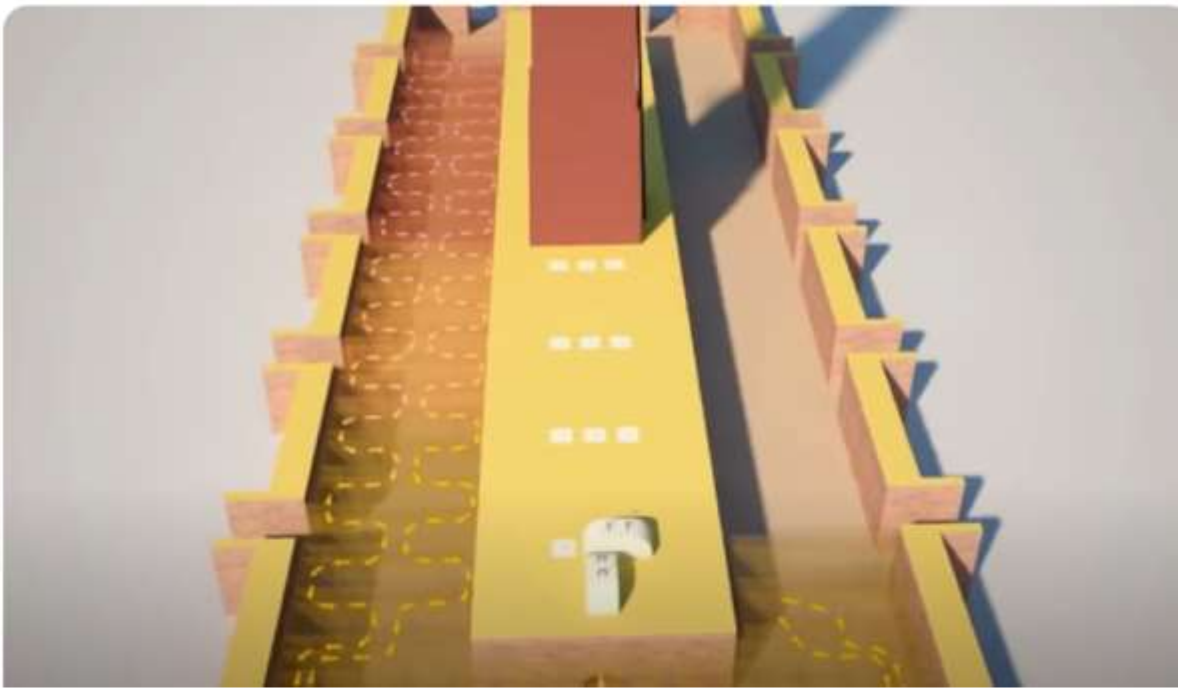

Figure 3.9: Zig Zag pattern of firing

Key learning

1. It is doable and payback period is fast
2. Improved kilns are energy and emission efficient

Impacts

Air pollution reduction potential for a particular source

In Valleys like Kathmandu, where brick kiln emission contribute to upto 15% of the PM10, significant improvement in the techniques is expected to reduce the contribution of pollution from this sector. In comparison to Improved Downdraft Zigzag Kilns (IDZKs), Fixed Chimney Bull's Trench Kilns (FCBTKs) demonstrated lower CO2 emissions, similar levels of SO2 emissions, and higher emissions of PM2.5 and BC, as determined by emission factors (EFs) based on a 1 kg of fuel/fuel mixture used in the kilns. However, when we consider the EFs per kilogram of manufactured brick, it becomes evident that all measured pollutant emissions were notably lower. This highlights that transitioning from conventional straight-line kilns to the zigzag design has the potential to substantially mitigate PM2.5 and BC emissions. The extent of reduction varies depending on whether we calculate EFs per kilogram of fuel or per kilogram of fired brick. Calculations based on EFs per kilogram of fuel indicate an approximate 20% reduction in PM2.5 emissions and a 30% reduction in BC emissions. Conversely, when measured per kilogram of fired brick, these reductions are even more significant, at around 40% for PM2.5 and 55% for BC. Given these estimations, the conversion of kilns from straight-line to zigzag configurations emerges as a promising avenue for emission reduction, fostering cleaner and more efficient brick-making technology (Nepal et al., 2019).

Socio- economic effects

As such building better brick kilns with reduced can bring in certain occupational health benefits. However large cohorts are required to prove the same. At the same time, only continued efforts and awareness for the brick kiln owners might bring in certain socio-economic benefits. In this area organizations like ICIMOD are in continuous dialogue with various agencies including banks, educational organizations and brick kiln owners to provide better facilities for the kiln workers.

Implementation

Success stories

[Brick Kilns | Building Back Better - YouTube]

Scalability and replicability

A directive was passed from the Government of Pakistan prohibiting the operation of all traditional kilns in the state between October and December 2018 based on various research in the region that the emission from these sources were contributing to the infamous winter fog. Meanwhile ICIMOD had started organizing trainings for converting traditional kilns to zig zag technology. Following this only a few traditional kilns were converted into zig zag and slowly steadily, this process keeps growing. Till date 100% of the kilns within the Kathmandu Valley are converted into the Zig Zag technology. Payback period ranges between 2-3 years.

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Pakistan Suspends Brick Kilns to Curb Pollution Ahead of Smog Season (globalcitizen.org)

South–South business partnerships towards energy-efficient and low-emission brick production in Pakistan - ICIMOD

https://www.youtube.com/watch?v=OUM5AMEtCqA

BP5: Conversion of traditional diesel run waste picking 4 wheeler vehicle to electric 4 wheeler vehicles

Details of technology

Electric Vehicles (EVs) are fueled by electricity stored in batteries rather than traditional internal combustion engines (ICE) that rely on petrol or diesel. EVs have gained significant attention in recent years as a cleaner and more energy-efficient alternative to conventional vehicles.

Origin

The concept of electric vehicles dates back to the early 19th century, with several inventors experimenting with electric-powered cars. However, it was only in the late 20th and early 21st centuries that EVs gained popularity as a practical and sustainable transportation option. Advances in battery technology, environmental concerns, and the desire to reduce dependence on fossil fuels have driven the resurgence of electric vehicles.

Working/ Implementation

1. **Battery Charging:** EVs are charged by plugging them into an electric power source, typically through charging stations or home chargers. Charging can be done using standard electrical outlets (Level 1), home chargers (Level 2), or fast-charging stations (Level 3).

2. **Battery Energy Storage:** The energy from the charger is stored in a high-capacity lithium-ion or other advanced batteries within the vehicle.

3. **Electric Motor:** When the driver activates the accelerator pedal, electricity from the battery is sent to the electric motor, which converts it into mechanical power to drive the vehicle's wheels.

4. **Regenerative Braking**: EVs often feature regenerative braking, which recovers energy when slowing down or braking, sending it back to the battery for reuse.

Results

- Reduced Greenhouse Gas Emissions: EVs produce no tailpipe emissions, reducing greenhouse gas emissions compared to traditional vehicles.
- Lower Operating Costs: EVs typically have lower operating costs because electricity is cheaper than gasoline, and maintenance costs are often lower due to fewer moving parts.
- Quiet and Smooth Operation: EVs are quieter and provide smooth acceleration, contributing to a quieter and more comfortable driving experience.

Table 1. Comparison of US and EU vehicle emission standards with emissions from selected gasoline ICE vehicles and BEVs, and non-exhaust brake wear and tire wear emissions

	mg/km				
	$PM_{2.5}$	NO_x + HC	NO_x	SO_2	CO
Vehicle standards (test cycle)					
US Tier 3	2	53		0.6[a]	1057
Euro 6 (gasoline)	0.3[b]	170	60		500
Euro 6 (diesel)	0.3[b]		80		
US 2017 ICE					
Best-in-class (HEV) (test cycle)[42]	0.06[c]	2	0.3		31
2016 fleet average[d] (on-road)[10]		66	28		231
EU ICE					
Average Euro 6 gasoline DI ICE (RDE)[43,44]	0.2–0.4[b]		12–20		17–100
Typical 2017 BEV electricity emissions					
2014 US elec. grid[45–47]	7	71	70	123	
2016 US elec. grid[41]			37	41	
2030 US elec. grid[41]			30	32	
Brake and Tire Wear[50–52]					
Brake wear	2–6				
Tire wear	1–5 ($PM_{2.5}$)				
	4–13 (PM_{10})				

[a]Based on 5 mg S/kg fuel, fully converted to SO_2 during combustion, 8 L/100 km (29.4 miles per gallon)
[b]Based on particle number standard of 6×10^{11} #/km; 2×10^{12} #/km equals 1 mg/km. PM mass standard is 4.5 mg/km
[c]Total PM
[d]Chicago, IL area; assumed 22 miles per gallon gasoline [FHWA Highway Statistics 2016, Table VM-1]

Figure 3.10: A comparison of vehicle emissions at EU and US

A comparison of vehicle emissions at EU and US indicates that benefits of going completely electric. However there still exists a challenge of reducing emissions at the apex level that is where the power is generated. In this aspect the Indian government is increasing the share of electric generation from renewable sources or other clean energy sources and at the same time efficient control measures at the existing plants are also being implemented. So that at some point of time the excess energy requirement due to EV integration shall be completely met with clean energy generated at the sources. Hence, making the air quality improvement concrete (Winkler et al., 2018).

Impacts

- Environmental Benefits: EVs can reduce air pollution and greenhouse gas emissions, especially when powered by clean energy sources.
- Energy Security: Reducing dependence on oil for transportation enhances energy security.
- Economic Growth: The EV industry has created jobs and economic growth in various regions.
- There is also major climate and economic co-benefit of integrating EV fleet in developing nations (Ref: Electric Vehicles: An Economic and Environmental Win for Developing Countries (worldbank.org))

Pros and Cons /viability

Pros	Cons
Environmentally Friendly: Zero tailpipe emissions.	Limited Range: EVs may have limited driving range compared to gasoline vehicles.
Energy Efficiency: High energy efficiency.	Charging Infrastructure: Limited charging infrastructure in some areas.
Lower Operating Costs: Reduced fuel and maintenance costs.	Charging Time: Longer refueling time compared to gasoline vehicles.
Quiet and Smooth: Silent operation and smooth acceleration.	Upfront Cost: Higher upfront purchase price compared to some conventional vehicles.
Incentives: Many regions offer incentives for EV adoption.	

Challenges

Limited Driving Range: Overcoming range anxiety by increasing battery capacity.
Charging Infrastructure: Expanding charging networks to support widespread adoption.
Battery Technology: Developing cheaper, more durable, and faster-charging batteries.
Manufacturing: Scaling up EV production to meet increasing demand.

Recycling and Disposal: Addressing the environmental impact of battery recycling and disposal.

Scalability and replicability

EV adoption is growing worldwide, with governments, automakers, and technology companies investing heavily in EV technology and infrastructure. The scalability of EVs depends on advancements in battery technology, charging infrastructure development, and policy support to accelerate the transition from internal combustion engines to electric propulsion systems. The goal is to achieve widespread adoption and make EVs a viable and sustainable transportation solution on a global scale.

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BP6: Best Practices in the Integrated Fly Ash Management

Fly Ash produced during combustion of coal and transported from the combustion chamber by exhaust gases is a major source of waste materials and fine particulate pollution and may contain particles of hazardous nature (detrimental to human health). It is a pollutant which can contain acidic, toxic and radioactive components (Sonwani et al., 2023). Therefore, fly ash management remains a critical environmental and economic challenge in South and Southeast Asia. The best practice in this context, which stands out for its viability, business model, replicability, cost-effectiveness, and potential to reduce air pollution, is the **Integrated Fly Ash Management System**. The integrated fly ash management approach adopted by NTPC Limited in India is one of the best comprehensive models highlighting both viability and social acceptability.

Viability

- Economic Viability: The Indian power sector produces about 226.1 million tonnes of fly ash annually, with a utilization rate of around 78% (Central Electricity Authority, 2020). The vast generation of fly ash provides an economic opportunity for its utilization in various industries. For instance, the cement industry, which consumes about 25% of the total fly ash produced, benefits from reduced costs of raw materials.

- Technical Viability: NTPC has invested in state-of-the-art technology for the collection, transportation, and utilization of fly ash. These technologies include dry electrostatic precipitators (ESPs) for ash collection and pneumatic systems for transportation, ensuring efficient and environmentally friendly handling of fly ash.

- Environmental Viability: Fly ash utilization significantly reduces the need for landfills, thus limiting environmental degradation. The conversion of fly ash into eco-friendly building materials, like bricks and tiles, contributes to sustainable development. The Dadri power plant of NTPC in Uttar Pradesh, India, is a prime example of viable fly ash management. The plant achieved nearly 100% utilization of fly ash by supplying it to various industries, including cement and brick manufacturers (NTPC Annual Report 2021).

Social Acceptability

NTPC has actively involved local communities and stakeholders in its fly ash management processes. This has been crucial in gaining social acceptance. Information campaigns, stakeholder meetings, and demonstrations of the benefits of fly ash utilization have been key strategies.

- In Raigarh, Chhattisgarh, a fly ash brick manufacturing unit was established by NTPC, which not only utilized the fly ash from the nearby power plant but also created employment opportunities for the local population. The project gained wide acceptance and appreciation from the local community.

Business Models Associated with Best Practice in Fly Ash Management

The business model underpinning the successful management of fly ash at NTPC Limited in India has proved to be multifaceted, focusing on creating a sustainable and profitable ecosystem around fly ash utilization. This model can be dissected into several key components:

- Sale of Fly Ash: NTPC has established a revenue stream by selling fly ash to cement manufacturers, construction companies, and other industries. For example, in the fiscal year 2018-19, NTPC generated revenue of approximately INR 97 crores (around USD 13 million) from the sale of fly ash (NTPC Annual Report, 2018-19).

- Fly Ash-Based Products: The company has ventured into manufacturing bricks and other construction materials from fly ash. These products are not only environmentally friendly but also commercially viable.

- Agricultural Applications: Fly ash is marketed for agricultural use, improving soil quality and crop yield.

- Reduction in Waste Management Costs: By selling fly ash, NTPC reduces the costs associated with ash pond maintenance and management. This also mitigates environmental risks associated with ash ponds.

- Joint Ventures with Cement Companies: For example, NTPC has formed joint ventures with cement companies for the utilization of fly ash in cement manufacturing. This not only ensures a steady demand for fly ash but also promotes environmentally friendly practices in the cement industry.

- Collaborations for Fly Ash Brick Manufacturing: Small and medium enterprises (SMEs) are engaged in producing fly ash bricks, with technical and sometimes financial support from NTPC.

- NTPC Dadri: This plant has set exemplary standards in ash utilisation. NTPC Dadri achieved nearly 100% ash utilization, supplying fly ash to various cement plants and brick manufacturing (NTPC Report, 2019).

- NTPC Rihand: This plant utilizes dry ash extraction and ash water recirculation systems, significantly reducing water consumption and enhancing fly ash quality for commercial use.

Replicability in the Region

Based on the larger dependence of the South and Southeast Asian countries on thermal power plants for their energy requirements, the replicability of NTPC's Integrated Fly Ash Management System is promising, given the similarity in industrial and environmental contexts. Countries in South and Southeast Asia share common challenges related to fly ash disposal, including environmental degradation and the need for sustainable waste management solutions.

- Vietnam: The Pha Lai Thermal Power Plant in Vietnam adopted a fly ash management system inspired by NTPC's model. It resulted in an annual utilization of approximately 60% of the fly ash generated (Vietnam Energy Magazine, 2021).

- Bangladesh: The Barapukuria coal-based thermal power plant implemented a similar system, focusing on utilizing fly ash in cement and construction, which enhanced the fly ash utilization rate to around 50% in 2020 (Bangladesh Power Development Board, 2020).

Cost Benefit Analysis

- Reduced Landfill Costs: By utilizing fly ash, the costs associated with ash pond maintenance and landfilling are significantly reduced. For NTPC, this translates into annual savings of approximately INR 100 crores (USD 13.3 million) (NTPC Annual Report, 2018-19).

- Lower Raw Material Costs: In construction and agriculture, using fly ash reduces the demand for traditional raw materials, leading to cost savings. In cement production, for every ton of fly ash used, the cost of cement production is reduced by about 10% (Cement Manufacturers Association, India, 2020). The inclusion of fly ash reduced the clinker requirement by 25%, leading to a cost reduction of about 15% per ton of cement produced (Cement Manufacturers Association, India, 2020).

- Revenue Generation: The sale of fly ash provides a new revenue stream for power plants. In the case of NTPC, the revenue from fly ash sales reached INR 97 crores (USD 13 million) in the fiscal year 2018-19 (NTPC Annual Report, 2018-19).

- Job Creation: The fly ash industry creates jobs in ash brick manufacturing, transportation, and other related sectors. A study by the Confederation of Indian Industry (CII) estimates that every small-scale ash brick manufacturing unit employs around 10-15 people (CII, 2019).

- A project initiated by the Indian government involved using fly ash for constructing a 100 km stretch of road. The project led to a 30% reduction in construction costs compared to conventional methods and enhanced road durability (Ministry of Road Transport and Highways, India, 2021).

Reduction of Air Pollution and GHG Emissions

Air pollution reduction is one of the most significant benefits of effective fly ash management. In the context of NTPC's Integrated Fly Ash Management System in India, the potential to mitigate air pollution is substantial.

- According to a report by the World Bank (2020), using fly ash in cement production reduces CO_2 emissions by about 0.9 tonnes for every tonne of fly ash used. In India, NTPC has partnered with several cement manufacturers, leading to a significant reduction in carbon footprint. Considering that India's cement industry is the second-largest in the world, the incorporation of fly ash substantially lowers global CO_2 emissions. For example, if 50% of the cement produced in India uses fly ash, it could lead to a reduction of approximately 45 million tonnes of CO_2 annually.

- NTPC has initiated the covering and greening of ash ponds. In one of the NTPC plants, after implementing such measures, particulate emissions were reduced by around 30% in the nearby areas (NTPC Environmental Report, 2018). NTPC has also implemented Flue Gas Desulphurization (FGD) technology, which reduces SO_2 emissions. This process generates FGD gypsum, a by-product that can be utilized in the same way as fly ash. NTPC's thermal power plants, FGD implementation has resulted in a reduction of SO_2 emissions by approximately 80% (NTPC Sustainability Report, 2019).

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BP7: Paving of Roads and Mechanized Sweeping

One of the most notable examples of best practices in road paving and mechanized sweeping in South and Southeast Asia is from Singapore. The city-state is renowned for its clean streets and has incorporated an innovative and systematic approach to road maintenance and street sweeping

Technology Details

Singapore utilizes state-of-the-art road paving technologies such as stone mastic asphalt which provides durability and noise reduction. The mechanized sweepers used are equipped with GPS for route optimization and have vacuum and brush systems that are effective in both wet and dry conditions. The technology also includes air pollution control measures to prevent dust from being released during the sweeping process. Singapore's integrated approach, combining policy, public participation, and advanced technology, makes it a leading example of urban cleanliness. However, for other cities in the region with varying levels of resources, the key to replication lies in adapting the underlying principles of Singapore's model—such as strong governance, public-private partnership, and use of technology—rather than copying the model exactly.

Figure 3.11: Mechanised Road Sweeping Machine in Singapore (Source: Press Box, 2023)

Viability and Social Acceptability

Singapore's practice is highly viable due to the government's commitment to urban cleanliness and public health. The country has strict laws and regulations in place that mandate cleanliness, and there is high social acceptability due to the population's appreciation for the high living standards associated with clean streets. The National Environment Agency (NEA) oversees the implementation of these practices, ensuring consistency and high standards.

Business Models

Singapore's approach to urban cleanliness and road maintenance involves a hybrid model where the government sets strict regulations and standards while outsourcing certain services to private companies through public-private partnerships (PPP). The business model functions through a competitive tender process that awards contracts based on a mix of cost and quality criteria.

The government entity in charge of maintaining the cleanliness of roads, the National Environment Agency (NEA), typically publishes tenders for various urban cleanliness services. Companies then bid to offer these services, which may include road resurfacing, maintenance, and mechanized sweeping. The private companies involved in such practices operate under a Service Level Agreement (SLA) which stipulates the standards they must maintain. These standards are meticulously set by the NEA and include:

- Frequency of road sweeping and resurfacing
- Types of materials and technologies to be used
- Efficiency measures like waste reduction during sweeping
- Noise levels and other environmental impact considerations

The Land Transport Authority (LTA) has been involved in the testing and implementation of new road technologies that improve durability and are more sustainable. These models incentivize the private sector to not only provide the service efficiently but also to minimize waste and maximize the reuse of materials. This comprehensive approach helps Singapore maintain its reputation for cleanliness and efficiency, while also fostering a competitive market for environmental services. The business models are designed to be sustainable, ensuring that the private companies remain profitable while delivering high-quality services, and are built with enough flexibility to adopt innovative technologies as they become available.

Replicability

Singapore's model emphasizes integrated urban management and can be replicated in other urban areas in the region with adjustments for local contexts. Its success hinges on strong governance, a culture of cleanliness, and public-private collaboration. Other cities in the region can adopt this model, focusing on the structured and accountable aspects of the practice.

- **Policy and Governance:** Singapore's interagency collaboration is critical for replicability. The Land Transport Authority (LTA), Urban Redevelopment Authority (URA), and NEA work in synergy, allowing for comprehensive planning and execution. For replication, other cities in the region must establish strong governance frameworks, possibly through the creation of similar interagency committees or task forces that oversee urban cleanliness and infrastructure development.

- **Financial Models:** Singapore often employs a "user pays" principle, where the costs of public services like waste management and street cleaning are partially recouped through fees and fines. This ensures that there is a sustainable funding stream for these services. This principle can be adapted in different contexts where the fee structures are aligned with the local economic realities.

- **Public-Private Partnerships (PPPs):** The country has leveraged PPPs to finance and manage its road and street maintenance operations effectively. By allowing private companies to bid for these contracts, Singapore ensures competitive pricing and innovative solutions. This PPP model can be adopted by other countries, with adaptations based on local legal frameworks and market conditions.

- **Technology Transfer and Adaptation:** Singapore has invested in advanced technologies for road paving and street cleaning, which are more efficient and environmentally friendly. While the direct transfer of such technologies might not be feasible for all regions due to cost constraints, the underlying principles of using efficient and sustainable technologies can be applied. Cities in the region can start with more basic mechanized systems and gradually scale up as resources allow.

- **Training and Development:** A critical aspect of Singapore's model is the emphasis on skilled labour for operating complex machinery. For effective replication, workforce training programs are essential. This could include partnerships with educational institutions to certify workers in the operation and maintenance of street sweeping technology.

- **Environmental Considerations:** Singapore's approach is tailored to its tropical climate, which requires frequent street cleaning to prevent the buildup of mould and debris that can lead to urban flooding. In replicating this practice, other cities would need to consider their local environmental conditions, adjusting the frequency and methods of street cleaning accordingly.

Cost-Benefit Analysis

The cost of implementing such systems is relatively difficult and is largely offset by the long-term benefits of a clean urban environment and air quality. While the initial investment in technology and infrastructure can be significant, the benefits include improved public health, enhanced tourism appeal, and reduced environmental damage. In Singapore, the exact cost figures are proprietary, but the visible cleanliness of the city suggests a positive return on investment.

Potential to Reduce Air Pollution

Singapore's streets are some of the cleanest in the world, contributing to its consistently good air quality indices relative to other major cities in Asia. Singapore has consistently been lauded for its excellent air quality and urban cleanliness, which is a direct result of its systematic approach to environmental management. Air quality in cities is often compromised by a variety of pollutants, with particulate matter (PM) being among the most harmful. Particulate matter can originate from various sources, including construction sites, industrial activities, vehicular emissions, and road dust.

- Singapore's National Environment Agency (NEA) has implemented a comprehensive set of measures to control dust and other emissions from construction sites and roads, which includes the requirement of regular sweeping. According to the Sustainable Construction guidelines by the Building and Construction Authority (BCA) and NEA, it is mandatory for construction sites to implement effective dust control measures, which indirectly relate to the city's overall air quality management. The NEA monitors PM2.5 closely and reviews the status periodically.
- In terms of the direct correlation between street sweeping and air quality, detailed data is not often publicly available as it is challenging to isolate the impact of street sweeping from other factors that contribute to air quality. However, the implementation of these practices is part of Singapore's broader environmental policy, which has shown overall success in maintaining a clean and healthy urban environment.
- Singapore's mechanized sweepers are designed to be less intrusive, emitting less noise and themselves being low on emissions, which further aids in the reduction of overall air pollution.
- Sweepers are typically equipped with fine water mists to trap particulate matter and prevent it from becoming airborne during the cleaning process.

The continuous improvement in Singapore's air quality over the years is the best example of the effectiveness of its integrated approach, which includes mechanized street sweeping. Such improvements are significant, given the dense urban setting and the potential for high levels of vehicular and industrial pollution.

Case study

Although a detailed public data specifically isolating the impact of street sweeping on air quality in Singapore seems limited. However, the overall improvement in Singapore's air quality indices and urban cleanliness suggests the effectiveness of its comprehensive environmental policies, of which mechanized sweeping is a part. For a robust implementation of this solution elsewhere, similar studies or pilot projects could be conducted to gather local data. These studies should focus on measuring specific air quality parameters before and after the implementation of mechanized sweeping and improved road paving technologies. This would provide a strong, context-specific basis for assessing the strategy's effectiveness.

In Delhi, India, mechanized road sweeping has been implemented, sweeping over 26.17 km per shift, though no efficacy study for reduction of air pollutants due to these mammoth machines are yet available (Manuja et al., 2020).

Elliot et al., (2023) have quantified and compared the environmental impacts of three road rehabilitation scenarios in Ontario, Canada, using life cycle assessment for one lane-km of road over a 30-year estimated service life.The study found that RAP100, which deploys Cold In-place Recycling (CIR) technology using reclaimed Asphalt Pavement (RAP) and bitumen emulsion finished with a Hot Mix Asphalt (HMA) wearing course, with a 15-year rehabilitation cycle is a superior approach if climate change and material scarcity are considered into the environmental criterion. The GWP associated with RAP100 is only about 144 tonnes CO2-eq in comparison to 620 for China and 260 for South Africa. It generates only upto 44 kg CO2-eq per tonne over a 30-year estimated service life.

In a study by Yee (2005), comparing data from cities of Berkeley and Oakland in California, with and without road sweeping (opt-out program), it was observed that although pollutant levels on road surfaces were site specific, some opt-out streets had distinctly higher levels of sediments and/or pollutants. Between mechanical and regenerative air sweeper equipment, the later ones blast air onto the street to loosen particles and are more effective in removal of fine particles, but do not pick up larger particles effectively. In this scenario, the remaining sediment can become fine-grained with time and contribute to air pollution. As per our discussions with an expert it is important to account for the swept dust and bury/reutilise them for good, otherwise it is a case of just transporting the pollutant from one place to another; in most cases from centre of the road to shoulders.

In a study in Chiayi city (southwest Taiwan), it was found that the "sweeping before washing" strategy was the most effective operation mode compared to other strategies: clean sweeping and washing before sweeping (Lin et al., 2023). It resulted in suppression of the ultrafine particulate (UFP) by 42%. Results show the high PM2.5 mass and UFP number concentrations occur during the street washing, because of the street washing diesel-fueled vehicle's own emissions.

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BP8: Integrated solid waste management system

One of the notable examples of best practices in waste management that has been making strides in South and Southeast Asia, with a specific focus on air quality improvement, is the integrated solid waste management (ISWM) system implemented in Surabaya, Indonesia (UNEP 2017).

The city has implemented a comprehensive approach to waste management, where the waste is segregated at the source, with a significant emphasis on community participation.Organic waste is converted into compost, reducing methane emissions from landfill decomposition. Morevover, these facilities separate recyclables from the waste stream, reducing the volume of waste that goes to landfills and onversion of non-recyclable waste into energy, reducing the reliance on open burning and minimizing emissions.The success of Surabaya's model is evident in its high community participation rates, reduced landfill use, and integration of waste-to-energy solutions. The city has witnessed tangible benefits in terms of waste reduction, revenue generation from recyclables and compost, and extended landfill lifespans.

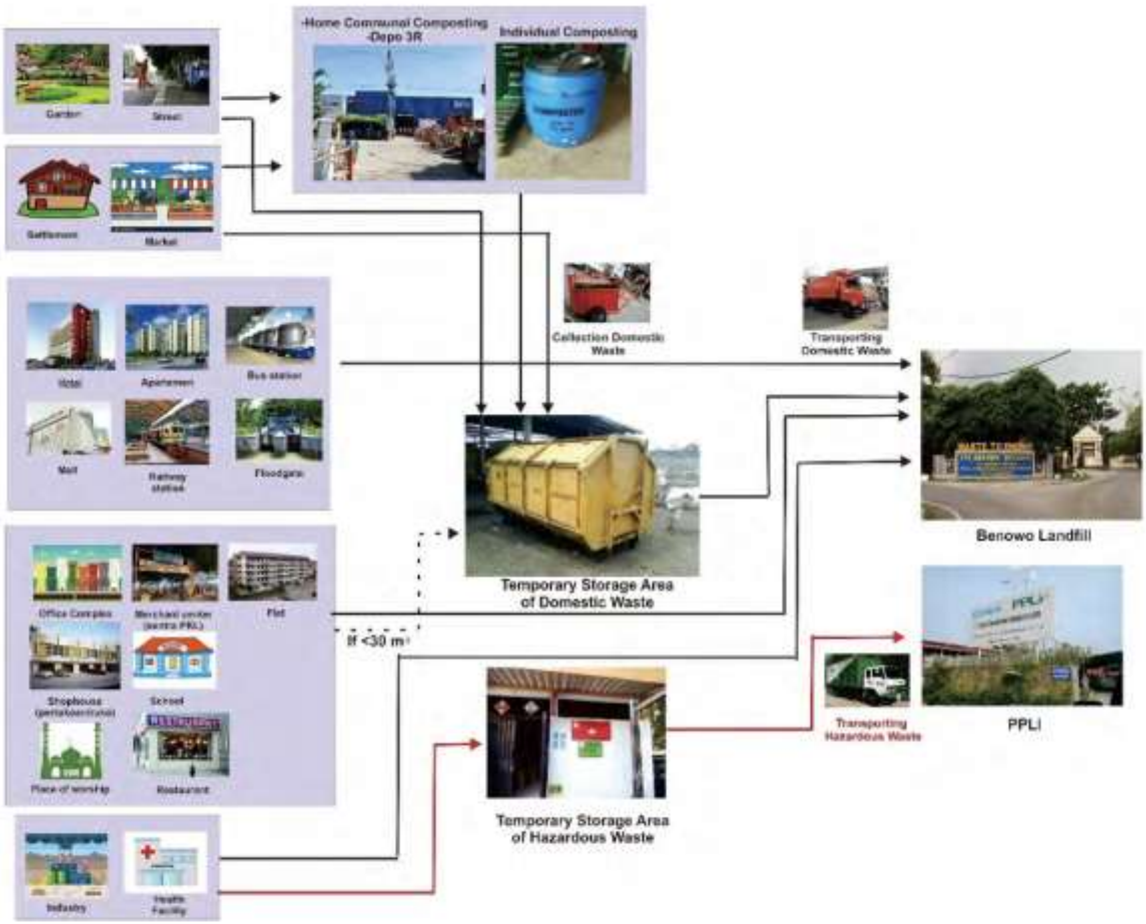

Figure 3.12: Surabaya Waste Management Flow (Source: UNEP: 2017)

Technology Details:

The technology involved in Surabaya's ISWM includes simple yet effective composting facilities and material recovery facilities (MRFs) that separate recyclables from waste streams. Low-tech solutions are favoured to ensure affordability and ease of maintenance. Additionally, the city has invested in more modern waste-to-energy technologies to manage non-recyclable waste.

Viability and Social Acceptability

Surabaya's ISWM system is considered socially acceptable and has high community participation rates. This system includes segregation at source, community-based recycling, and the conversion of organic waste into compost. The initiative has been successful due to strong community engagement and education programs that have encouraged public participation and awareness. The programs often involve local citizens in monitoring and managing waste, thereby ensuring that the solutions are culturally and socially attuned to the local context. Surabaya's approach to ISWM addresses multiple facets of waste management that directly or indirectly impact air quality in the following ways:

- The city's composting program not only reduces the volume of organic waste destined for landfills but also mitigates the generation of methane, a potent greenhouse gas often released by decomposing organic matter in anaerobic landfill conditions.
- The city also actively discourages the common practice of open burning of waste. Open burning releases a variety of pollutants, including particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), and polycyclic aromatic hydrocarbons (PAHs), all of which can degrade air quality and pose health risks to the population.
- The social acceptability of the ISWM program is closely linked to its impact on air quality and public health. Public education campaigns often emphasize the direct benefits to residents, such as reduced unpleasant odors and lower incidence of waste-related fires, which can contribute to haze and poor air quality.

Business Models

The Surabaya city government collaborated with small and medium enterprises (SMEs) and the informal sector for the collection, segregation, and recycling of waste. The sale of recyclables and compost generates revenue, which supports the sustainability of the business model. Additionally, the system saves municipal funds by reducing the frequency of waste collection needed due to effective source separation and recycling.

- The business model of Surabaya’s waste management system is intricately linked to improving air quality through the reduction of open burning and the diversion of organic waste from landfills, which can reduce the production of methane, a potent greenhouse gas.

- Surabaya's model has integrated the informal sector into the formal waste management system, employing individuals who previously may have resorted to burning waste as a disposal method. By providing these workers with stable income and formalizing their roles in waste segregation and recycling, the city has reduced the instances of open burning, a significant source of air pollution.
- The business model supports the composting of organic waste, which is sold to local farmers and gardeners, creating a stream of income. Composting reduces the release of methane from organic waste decomposition in landfills. Methane has a global warming potential 25 times greater than carbon dioxide over a 100-year period, according to the Intergovernmental Panel on Climate Change (IPCC). By diverting organic waste to composting facilities, the system significantly lowers the potential for air pollution.
- Waste-to-Energy (WtE) Technologies: Where composting is not viable, Surabaya has looked towards waste-to-energy technologies. These facilities can convert waste into electricity or fuel, thus providing an additional revenue stream while also ensuring that waste disposal does not contribute to air pollution through burning. Properly managed WtE facilities adhere to strict emission standards, mitigating the release of pollutants into the atmosphere.
- Surabaya's ISWM system has been supported through PPPs, which allow for private investment in waste management technologies that are more efficient and less polluting. These partnerships help finance the initial capital outlay for advanced technologies, which can often be a barrier for municipal governments. Through PPPs, businesses can recover their investments over time via long-term contracts for waste processing.

Replicability

The Surabaya model emphasizes community involvement and SME partnerships, which are common and replicable structures across Southeast Asia. By adapting the model to local contexts, other cities in the region could implement similar systems. Technical support and knowledge sharing from Surabaya's municipal government to others in the region could facilitate this replication.

Cost-Benefit Analysis

A cost-benefit analysis of the Surabaya system would include savings from reduced landfill use, revenue from recycled materials, and reduced health costs from improved air quality. Although detailed numbers are subject to periodic assessments, initial reports suggest that the city has reduced its waste collection costs significantly and extended the life of its landfills, resulting in long-term financial savings.

The tipping fee at the landfill is significantly deterrent at IDR140,000 (US$10 in February 2017) per tonne, with total disposal per annum being approximately 467,565 tonnes for a total cost of approximately US$4.7m. As disposal poses a significant cost to the city's exchequer, the large savings potential needs to be harnessed through waste reduction and diversion activities.

- Substantial savings to the city would be possible through reform of the waste management system both in reduction of waste at source and an improvement of and increased coverage of intermediate facilities.
- 60 people were to be hired for non-organic and 10 people were to be hired for organic waste management. Assuming that sufficient facilities were established to cover all of Surabaya's waste management, it would require a total of 382 people to manage the non-organic waste and 86 people to manage the organic waste, a total of 468 people.
- Assuming they were hired at the minimum wage, IDR 2.1m per month (US$157 in February 2017), that would be a total wage cost of US$73,476 per month or US$881,172 per year.

Potential to Reduce Air Pollution

Surabaya's integrated solid waste management (ISWM) system, revolves around several key interventions that can support for reducing air pollution. Some of the interventions with high potential for air quality management are:

- **Waste-to-Energy Technologies**: Where composting isn't applicable, Surabaya has explored waste-to-energy (WTE) solutions. Modern WTE facilities can greatly reduce the volume of waste that requires disposal and can do so with relatively low emissions compared to open burning, which is a common practice in many developing regions. Open burning releases a wide range of pollutants, including particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO2), and volatile organic compounds (VOCs). All of these have detrimental effects on air quality and human health. WTE technologies in Surabaya, which are subject to emission controls, can reduce these pollutants significantly.
- **Diversion and Recycling:** By diverting recyclable materials from the waste stream, Surabaya's ISWM reduces the volume of waste that might otherwise be burned or landfilled. Recycling processes typically require less energy and produce fewer emissions than the manufacture of products from virgin materials. This can lead to reductions in industrial emissions of air pollutants, assuming that the energy used in recycling processes comes from relatively clean sources.
- **Emission Controls and Regulations:** Surabaya has implemented regulations that mandate certain standards for waste management practices, including emissions

from WTE plants. These regulations help ensure that any incineration is done with proper air pollution control technologies, such as scrubbers, filters, and catalytic converters, to minimize the release of harmful pollutants.

To further substantiate this model's effectiveness for air quality management, a comprehensive study or assessment in Surabaya or similar implementations could be conducted, focusing on measuring specific air quality parameters and correlating them with waste management practices. This would provide a more concrete basis for assessing the impact of ISWM systems on air quality.

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BP9: Solar Parks and Rooftops

Solar Parks

Solar parks are vast areas of land dedicated to hosting large-scale solar power installations. These are centralized facilities that can generate hundreds of megawatts (MW) of power, feeding into the national grid and thus replacing or reducing the need for conventional coal-based power generation. India's development of solar parks is a cornerstone of its strategy to harness renewable energy, making it a critical element in the nation's approach to curbing air pollution and advancing towards a more sustainable and clean energy future. India has been aggressively developing solar parks as part of its National Solar Mission to ramp up its renewable energy capacity. Here are some notable success stories of solar parks across the country:

- Bhadla Solar Park, Rajasthan: Spanning over 14,000 acres, Bhadla Solar Park is one of the largest in the world, with an ultimate capacity of around 2,245 MW. The park is situated in a desert area with high solar irradiance, making it an ideal location for solar power generation.
- Pavagada Solar Park, Karnataka: Also known as the Shakti Sthala, this park has a total capacity of about 2,050 MW. It has been developed on barren land and has become a model for land utilization and solar development.
- Charanka Solar Park, Gujarat: Located in Patan district, this was one of the first solar parks developed in India. It is part of Gujarat's pioneering efforts in renewable energy and has multiple developers contributing to its capacity.

- Kamuthi Solar Power Project, Tamil Nadu: With a single location capacity of 648 MW, the Kamuthi solar plant was once the largest solar power plant in the world. It's not a solar park in the traditional sense with multiple developers, but it represents the scale of solar projects in India.
- Ananthapuramu Solar Park, Andhra Pradesh: This park is spread over several villages and, upon completion, aims to have a capacity of around 1,500 MW, contributing significantly to the state's renewable energy supply.
- Rewa Ultra Mega Solar, Madhya Pradesh: This solar park is known for its innovative financing and for breaking records in solar tariffs at the time of its auction. It has a capacity of 750 MW and supplies power to the Delhi Metro Rail Corporation as well as the state distribution companies.
- Kurnool Ultra Mega Solar Park, Andhra Pradesh: With a capacity of 1,000 MW, the Kurnool solar park was the world's largest solar park at one point. It plays a crucial role in Andhra Pradesh's renewable energy strategy.

These solar parks not only contribute significantly to India's renewable energy portfolio but also serve as a catalyst for the growth of the solar industry, providing numerous economic and environmental benefits. Each park leverages the scale of shared resources, infrastructure, and support services to lower the cost of energy production and minimize the barriers for new entrants in the solar power generation market.

Technology

- **Scale:** Solar parks in India are among the largest in the world. For example, the Bhadla Solar Park in Rajasthan and the Pavagada Solar Park in Karnataka have capacities of over 2,000 MW and 2,050 MW, respectively.
- **Infrastructure:** The government provides the necessary infrastructure, such as roads and transmission lines, to support the construction and operation of these parks.
- **Land Acquisition:** Solar parks help mitigate one of the biggest challenges in solar deployment — land acquisition. The government often facilitates this process, reducing the burden on developers.

Business Models

- **Public-Private Partnerships (PPPs):** Many of these parks are developed through PPPs, with the government providing land and infrastructure, while private firms install and manage the solar panels.
- **Subsidies and Incentives:** Developers often receive financial incentives, tax breaks, and subsidies to set up units in these parks, making them economically attractive.
- **Plug and Play Model:** By offering ready-to-use infrastructure, the 'plug and play' model in solar parks reduces the lead time for setting up new solar projects.

Reduction of Air Pollution

By centralizing solar power production, solar parks significantly contribute to India's renewable energy capacity, directly impacting air quality by:

- **Displacing Coal:** Each megawatt of solar power capacity installed in these parks potentially displaces a significant amount of coal-fired electricity, which is a major source of air pollution in India.
- **Reducing Emissions:** Solar parks contribute to a substantial reduction in emissions of sulfur dioxide, nitrogen oxides, and particulate matter, all of which are pollutants released by burning fossil fuels.
- **Setting Precedents:** The success of these parks has set a precedent, encouraging more renewable energy investments and signaling a shift away from polluting power sources.

To have a more tangible understanding of the impact of solar panels on reducing coal use for electricity production, some basic calculations suggest its key role in air pollution reduction. For example, a typical solar panel used in a large-scale installation might have a capacity of around 250 watts (W). The amount of electricity a solar panel can generate depends on its efficiency and the solar irradiance of the location. In India, if it is assumed that an average of about 5.5 hours of peak sunlight per day. It can significantly supplement and support in fulfilling energy needs apart from thermal power plants. Usually, coal-fired power plants have an efficiency of about 33% to 40%. So, with 100 solar panels, each of 250W capacity, operating under average conditions in India, it could potentially displace about 59 kg of coal per day. This simplified calculation and actual numbers can vary based on the specific efficiency of solar panels, local solar irradiance, and the type and efficiency of coal used but will greatly reduce the coal use and eventually the air pollution due to it (US-EIA, 2012).

Rooftop Solar

Rooftop solar refers to the installation of solar photovoltaic (PV) systems on the roofs of residential, commercial, institutional, or industrial buildings. This approach allows for the direct generation of electricity at the point of consumption, reducing the demand on the grid and the need for transmission infrastructure.

Microgrid and off-grid solar solutions are decentralized energy systems that are particularly valuable in remote and rural areas where the central electricity grid may not reach. These systems can operate independently or in conjunction with the main grid, and they provide a reliable and renewable source of electricity.

Technology

- Microgrid Solutions

  A solar microgrid is a small-scale power grid that can operate independently or in conjunction with the area's main electrical grid. It typically includes solar panels, battery storage, and a control system. Microgrids are designed to serve a small localized group of consumers, such as a village, an island, or a particular locality.
- Off-grid Solutions

  Off-grid solar solutions are not connected to the main power grid at all. These systems are often used in areas where it is too remote or too expensive to extend the main grid. Off-grid solar systems will typically include solar panels, battery storage, and an inverter to convert the solar panel's DC output into AC electricity for home or business use.
- Smart Power India: Supported by the Rockefeller Foundation, Smart Power India has facilitated the development of microgrids in several states in India, providing electricity to thousands of rural beneficiaries and businesses.
- SELCO India: SELCO has implemented sustainable energy solutions including solar lighting and water heating systems in rural parts of India, demonstrating the viability of off-grid solar solutions for enhancing quality of life.

- Tata Power's Microgrids: Tata Power has established microgrids that supply solar-based power to rural communities, which helps in reducing carbon footprint and providing reliable power.
- Mera Gao Power: This company builds and operates solar microgrid utilities in Uttar Pradesh, providing affordable lighting and mobile charging services to off-grid villages.
- Rural Electrification Corporation (REC): REC has been involved in various projects to promote off-grid solar applications across India, providing power for lighting, water pumping, and small-scale businesses.

Business Models

The Indian government has actively promoted rooftop solar installations through various subsidies and incentives. These measures include:

- Financial subsidies that reduce the upfront costs of installation for homeowners and businesses.
- Feed-in tariffs or net metering policies, allowing consumers to sell excess power back to the grid, thus improving the economics of their investment.
- Solar city initiatives aiming to promote the adoption of solar power in urban areas.
- Technical support and simplified procedures for system installation and grid connection.

Viability

- Job Creation: The growth in rooftop solar installations has created jobs in manufacturing, installation, maintenance, and sales.
- Skill Development: It has spurred the development of skilled trades and engineering professions related to solar technology.
- Public Health: By reducing the need for fossil-fuel-based electricity, rooftop solar installations contribute to cleaner air and improved public health.

India has several notable examples of successful rooftop solar installations across different sectors, reflecting the country's commitment to expanding its renewable energy capacity. Here are a few examples:

Residential Rooftop Solar Installations

- Gujarat Solar Rooftop Programme: Gujarat has one of India's most successful rooftop solar programs. It offers subsidies to homeowners and has led to widespread adoption across the state.

Commercial and Industrial Rooftop Solar Installations

- Coimbatore's Textile Mills: In Tamil Nadu, several textile mills have installed large rooftop solar systems to power their operations, reducing their reliance on grid electricity and cutting operational costs.

Institutional Rooftop Solar Installations

- IIT Bombay Solar Project: The Indian Institute of Technology (IIT) Bombay has a significant rooftop solar installation that powers its academic buildings and reduces its carbon footprint.

Government and Public Sector

- Solar Energy Corporation of India (SECI): SECI, under the MNRE, facilitates the implementation of various solar projects, including rooftop installations on government buildings.

Utility-Scale Rooftop Solar Installations

- Delhi Metro Rail Corporation (DMRC): DMRC has installed rooftop solar panels across various metro stations in Delhi, making it one of the greenest metro services in the world.

Corporate Rooftop Solar Installations

- Infosys Campuses: Infosys, one of India's leading IT companies, has installed large rooftop solar systems at many of its campuses across India as part of its sustainability goals.

Community and Rural Rooftop Solar Installations

- Chhattisgarh's Solar-Powered Villages: Chhattisgarh State Renewable Energy Development Agency (CREDA) has implemented rooftop solar solutions in remote villages, providing reliable electricity where grid connectivity is a challenge.

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BP10: Best Practices in Biomass Gasification

The Mitr Phol company in Thailand has one success story in the gasification of primary biomass that can be very useful in reducing air pollution due to the open burning of agro-residues. It is an agricultural by-product, and is a reliable and renewable source of biomass, providing a consistent feedstock for gasification processes without the need for significant additional raw material costs.

Viability

- Investing in advanced gasification technology ensures that the process is efficient and yields high-quality syngas suitable for energy production.
- It reduces reliance on external power sources. This not only provides energy security but also stabilizes operational energy costs, which is particularly important in a manufacturing environment with high energy demands.
- Gasification plants can be expanded modularly to increase capacity in line with increased production of biomass or energy demand.

- The current high electricity prices can make renewable energy production more profitable. Similarly, market demand for renewable energy can create favourable conditions for investments in gasification technologies.
- The process of converting bagasse into energy fits into the larger context of sustainable resource management. The use of biomass gasification contributes to a reduction in greenhouse gas emissions when compared to traditional fossil fuel-based energy sources. This aligns with global efforts to combat climate change and positions the company as a leader in sustainable practices.

Social acceptability

- The gasification project can be helpful in creating jobs, both during the construction phase and for the ongoing operation of the facility, contributing to local economic growth.
- By purchasing biomass from local farmers, including sugarcane bagasse or other agricultural residues, such a project can generate additional income for the local agricultural sector.
- Reducing the open burning of agricultural waste by converting it into energy not only has environmental benefits but also improves air quality, which has direct positive implications for public health.
- Such initiatives can also attract socially conscious investors and partners, and support from the broader society.

Business Model

- The business model could be integrative in nature, with sugar production (or other biomass) at its core. The biomass gasification aspect capitalizes on the by-products of sugar production—mainly bagasse, which is the fibrous matter that remains after sugarcane stalks are crushed to extract their juice. This integration ensures that the primary business generates the raw material for the energy production side, creating a closed-loop system that adds value to what would otherwise be waste.
- The gasification process converts biomass into a combustible gas (syngas), which is then used to produce electricity. This energy is primarily used to run the sugar mills, reducing the company's reliance on external energy sources and cutting

energy costs significantly. The surplus energy generated is a secondary product, providing an additional revenue stream through feed-in tariffs or direct sales to the power grid.

- Thailand's government offers various incentives for renewable energy production, including feed-in tariffs, tax incentives, and investment grants. So, the business model aligns with these incentives to ensure economic viability and compliance with environmental regulations, which reduces risk and improves the financial returns from their biomass gasification operations.
- By venturing into biomass gasification, there is an opportunity for diversification. This diversification is an excellent risk management strategy, making the business less vulnerable to fluctuations in sugar prices while providing a steady income from energy sales. This also means that the company is less exposed to the risks associated with fossil fuels, such as price volatility and supply disruptions.
- By leveraging biomass gasification operations, the business can enhance its competitive advantage. It not only markets itself as an environmentally responsible entity but also benefits from the positive branding associated with green energy, which can drive consumer preference and loyalty.
- The business model espouses circular economy principles by using all by-products and reducing waste. The ash from the gasification process, for instance, can be used as fertilizer, returning nutrients to the soil and improving the sustainability of the company's operations. This minimizes waste disposal costs and environmental impact, further strengthening the business case for biomass gasification.

Replicability

- Implementation of biomass gasification hinges on the deployment of specific technologies that convert biomass into syngas efficiently. The same technology can be used elsewhere, assuming similar operational conditions and technical expertise.
- The abundance and consistency of biomass supply are crucial. South and Southeast Asian regions can benefit from having a steady supply of biomass.

Potential sources include agricultural residues, wood waste, and organic municipal waste.

- Favourable regulations, subsidies, and incentives can significantly impact the success of similar projects. Feed-in tariffs, tax incentives, or carbon credit systems can make such projects more attractive to potential investors.
- The biomass gasification project likely has positive socioeconomic effects in other regions, providing jobs and supporting local economies.
- When replicating the model, similar community benefits are important for gaining social acceptability. Training programs and the development of local expertise in managing and operating gasification plants can also contribute to the long-term success of this type of project.

For India, the replication of biomass gasification projects like Mitr Phol's is feasible and aligns with the country's renewable energy goals. However, it requires careful planning, adaptation to local contexts, and supportive policy frameworks. The key reasons which support its replicability in India are based on the following points:

- India has a significant amount of agricultural residue, which is often burned, contributing to air pollution. Converting this biomass into energy through gasification could provide an environmentally friendly solution.
- The diversity of agricultural practices across India means a variety of biomass types are available, which could be utilized in gasification plants.
- India's focus on renewable energy and reducing greenhouse gas emissions aligns well with the adoption of biomass gasification technology.
- Biomass gasification could complement solar and wind energy, providing a stable and continuous source of energy.

However, there exists some specific challenges which also need to be taken care of:

- Developing robust and efficient gasification technology suitable for local conditions and biomass types.
- The initial investment for setting up biomass gasification plants can be substantial.

- Establishing a reliable supply chain for the collection and transportation of biomass to gasification plants.
- Managing the logistics of biomass collection from diverse and scattered sources can be challenging.
- Streamlining regulatory approvals and providing clarity on tariffs and grid connectivity for electricity generated from biomass.
- Addressing concerns related to the sustainability of biomass sourcing and ensuring it does not compete with food production.
- Managing social implications, such as the impact on local communities and employment opportunities.
- Providing training and support to farmers and local businesses involved in the supply of biomass.

Cost Benefit Analysis

- Capital Expenditure (CapEx): This includes the cost of acquiring the gasification technology, construction of the plant, and installation of related infrastructure.
- Operational Expenditure (OpEx): These are the ongoing costs for running the gasification plant, which includes maintenance, labour, utilities, and any necessary repairs or replacements of parts.
- Revenue can be generated by using the syngas to create electricity, which can be used for self-consumption, reducing the need to purchase energy from other sources. Any surplus electricity is sold back to the power grid, creating an additional income stream.
- By reducing greenhouse gas emissions, the project may be eligible for carbon credits under various international frameworks, which can be sold on carbon markets.
- Savings on energy consumption are substantial over time since the plant is using a waste by-product that would otherwise have little to no economic value.
- The integration of energy production with the main production process (sugar manufacturing) potentially makes the overall operation more efficient, thereby reducing costs.

Potential for Reducing Air Pollution

Biomass gasification is a thermochemical process that converts organic materials into a combustible gas mixture, typically referred to as syngas. This process involves partial oxidation at high temperatures. The syngas can then be used to produce electricity and heat or as a feedstock for producing chemicals. Here are the ways in which this technology can contribute to air pollution reduction:

- Traditional methods of disposing of agricultural waste often involve open burning, which releases a significant amount of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO2), and volatile organic compounds (VOCs) into the atmosphere. Gasification greatly reduces these emissions because it is a contained process with emissions control systems.
- Gasification of biomass is considered to be carbon-neutral because the CO2 released during the process is roughly equivalent to the amount absorbed by the plants during their growth. However, when compared to the carbon emissions from fossil fuels, the net contribution to atmospheric CO2 levels is lower.
- Utilization of Methane: During gasification, methane produced can be captured and used as a fuel rather than being released into the atmosphere. Methane has a global warming potential that is many times greater than that of CO2, so capturing and utilizing this gas is significantly beneficial for climate change mitigation.
- Gasification plants can be equipped with advanced emissions control systems that can remove contaminants from the syngas before combustion. This is much more efficient compared to controlling emissions from direct biomass burning or from older, less efficient coal-fired power plants.
- By providing a use for agricultural residues, gasification encourages sustainable agricultural practices. It gives farmers an incentive to manage waste responsibly rather than burning it in an uncontrolled manner, which can have a significant local air quality impact.

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Chapter 4
Nature Based Solutions

General Understanding

Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions." -The European Commission

Most of the nature based solutions (NBS) promote air pollution reduction in 3 primary ways:

- Absorption of air pollutants by plants through physical, physiochemical and biological means e.g. dry deposition of O3 and PM on leaf surfaces, diffusion of CO2 through stomata.
- Trapping/ capture of Carbon
- Cutting off anthropogenic emissions as needs are replaced by natural solutions

Further, it has been observed that plant emissions are quite effective in cleansing the atmosphere through better recycling mechanisms for OH radical, the detergent of the atmosphere (Mallik et al., 2018).

Historical Overview

In this world full of a myriad of environmental challenges, the concept of NBS has emerged as a flicker of hope. These innovations are grounded in the utilization of natural resources to offer a pathway to address environmental issues.

The earliest instances of NBS can be traced back to the Indus Valley Civilization (3300–1300 BCE) where sophisticated water management systems utilized natural watercourses for irrigation, flood control, and drinking water supply. Similarly, the Mayans in Central America ingeniously used forests and wetlands to manage water resources, mitigating droughts and floods. During the late 20th century, projects such as Everglades restoration in Florida or the Rhine River rehabilitation in Europe brought NBS into trend for ecological restoration.

The historical trajectory of NBS gives us an intrinsically sustainable and resilient way of addressing environmental challenges. The integration of natural systems into urban planning has been efficient in enhancing the ecology and environmental challenges. As the climate crisis takes ugly turns every year, NBS stands as a timeless and adaptable approach to tackle this unprecedented destruction. The enduring partnership between humanity and the natural, paves a way of sustainability and coexistence.

Current Practices

Nature based solutions are being steadily implemented in many regions of the world. NbS appear to be the most appropriate remedy for environmental issues of urban areas, particularly in developing countries due to their multi-functional and sustainable naure accentuated by cost-effectiveness. NbS in addition to reducing urban heat and air pollution, also provides a wide range of co-benefits such as reducing energy cost and health costs as well as conservation of biodiversity (Menon & Sharma, 2021); Further, green infrastructure plays a crucial role in Abhijith et al., 2017).

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11 selected NBS Impact Studies

NBS1 : Biofencing

About / USP of this technique

Biofencing or biological fencing or living fencing, is a sustainable and eco-friendly way of creating natural barriers or boundaries using living plants, trees, shrubs, hedges etc. It has proven impacts in controlling erosion, providing windbreaks, deterring wildlife, and mitigating air pollution. Biofencing can serve as an effective nature-based solution to address air pollution in urban and industrial areas.

The USP of biofencing lies in its innovative and sustainable approach to address the challenge of air pollution and scalability. As fencing is something that is not ornamental hence replacing the traditional fencing materials like concrete or metal, with biofencing not only reduces the usage of these materials but also enhances the biodiversity in the area.

As some bio fencing plants are known for their air-purifying qualities, they help to improve air quality in the vicinity. Apart from that as densely vegetated bio fences act as natural noise barriers, it is useful in reducing the noise pollution in urban environments.

It is one of the most cost - efficient, easy to maintain and climate friendly community projects that have come up in recent times. Its unique blend of ecological, aesthetic, and practical advantages makes it an increasingly popular choice for various applications.

Figure 4.1 A well established bio-fence of Agave **Image Credits :** CENTRAL SOIL AND WATER CONSERVATION RESEARCH AND TRAINING INSTITUTE,RESEARCH CENTRE..

Air Pollution Reduction potential

Biofencing seeks to harness the natural air-purifying capabilities of plants to offer a holistic pollution mitigation strategy. This approach shows a lot of potential for improving air quality, reducing pollutants, and enhancing the quality of life in urban spaces. Pioneering work has been done by Nowak et al (2007) to explore the potential of such urban forestry to mitigate pollution with only 11 % coverage of Chicago city of aerial coverage of 600 sq km, the reduction of pollutants have been outstanding and hence should be encouraged more.

Table 4.1: Air pollution mitigation potential of urban forest ecosystems

Pollutant/ Mitigation	Reduction Potential	References
PM10 Filtration	212 metric tons per year	**Nowak & Dwyer (2007)**
CO removal	15 metric tons of CO per year	
Ozone Mitigation	191 metric tons of O3 per year	
SO2 Removal	84 metric tons of SO2 per year	
NO2 removal	9 metric tons of NO2 per year	
Air Quality Improvement	Trees contributed to improved air quality, with average hourly improvements ranging from	

	0.002 percent for CO to 0.4 percent for PM10. Maximum hourly improvements reached up to 1.3 percent for SO2, with even higher localized improvements in areas with substantial tree cover.	

Implementation

Biofencing has been actively researched and piloted in various parts of the world. Studies have been employed in several African nations and also in India-Eastern Ghats districts of Orissa, Chhattisgarh and Andhra Pradesh. Similar endeavours were frequently observed by states of Himachal Pradesh, Uttarakhand and Rajasthan.

Success Story

The Great Green Wall of Africa (GGW) is a prominent biofencing project aimed at combating desertification, land degradation, and climate change. It started off with the mission of creating a massive belt of greenery across the Sahel region to reduce desertification and improve the livelihoods of local communities. It was launched in 2007 and is a long-term project with the goal of restoring 100 million hectares of land, creating 10 million jobs, and sequestering 250 million tons of carbon by 2030.

As per the African Union, the GGW has restored 18% of the target. It has contributed to increased agricultural productivity and food security in some areas. By sequestering carbon through reforestation and afforestation efforts, the GGW is helping to mitigate climate change. Various studies and research projects are ongoing to monitor and assess the ecological, social, and economic impacts of the Great Green Wall.

Figure 4.2: Great Green Wall Initiative **(Image Credits : UNCCD)**

Cost benefit analysis

A cost benefit study was done in the Bundelkhand region of India, where crop damage by stays and wild animals was a great issue (Kumar et al., 2022). Local practice known as "Anna Pratha," which involves releasing animals for open grazing did not help much to tackle it. Traditional protective measures like barbed wire fencing and conventional fencing have proven to be costly and require ongoing maintenance, leading to additional expenses for farmers. This has prompted the need for a cost-effective and long-term solution to mitigate the problem.

In response to this challenge, a study was conducted to evaluate the potential of using thorny bamboo (Bambusa bambos) as a bio-fence to deter stray and wild animals. After 21 months of planting, the bamboo plants reached a maximum height of 4.47 meters, with a clump spread diameter of 30.50 cm. The growth of the bamboo bio-fence depends on soil and management conditions.

Before the establishment of the bamboo bio-fence, significant crop losses were reported due to animal invasions. However, once the bamboo plants formed a closely spaced thicket, effectively creating a bio-fence, only two incidents of animal intrusion were reported in the following year (2021–2022), with no crop damage.

The initial cost to develop a bamboo bio-fence was estimated at INR 5,796 for a length of 100 meters, making it an economical and effective crop protection measure against damage by wild and stray animals. This study demonstrated that bamboo bio-fencing has the potential to minimize the issue of crop damage by wild and stray animals in a cost-effective and sustainable manner, benefitting both farmers and the environment.
Kumar et al., (2022) demonstrated that "planting bamboo (B. bambos) at a distance of 80.00 cm in a continuous trench can be an effective bio-fence to avoid man–animal conflicts and thus protect the crop against damage from stray and wild animals, which keep farmers stress-free within 1–2 years of establishment. The time period to obtain the closure canopy of the bamboo bio-fence for full-proof protection against animals depends on the edaphic conditions. Unlike the other practices of crop protection, the bamboo bio-fence may last more than 50 years."

Pros and Cons

Pros	**Cons**
Biofencing in certain aspects acts as a physical barrier to intercept airborne pollutants and also absorbs pollutants thereby improving air quality.	Biofencing is space intensive and cannot be readily employed in densely populated urban areas.
Biofencing is also observed to have positively impacted to reduce noise pollution.	It takes time to develop to its full potential. A fence may take several years to reach a certain stage where it effectively mitigates air pollution.

Biofencing is cost and energy-effective, low maintenance and aesthetic method compared to other pollution control.	While it may be effective against removal of pollutants like CO2, SO2 etc its range as a phytoremediator is limited.
Biofencing contributes to biodiversity and ecological habitat for wildlife.	Some fencing species may act as invasive to the local ecology and impact the biodiversity of the region.
Biofencing is also used as a way to reduce man- animal conflict in vulnerable regions.	

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NBS2 : Biochar

About / USP of this technique

Biochar is produced by thermal decomposition of biomass (such as wood, crop residues, and organic waste) by pyrolysis (Burning in absence of oxygen). It is known for its soil improvement properties, carbon sequestration, and enhanced agricultural productivity. Biochar has been used in various cultures since time immemorial but is gaining attention in recent times as a sustainable nature based technology. Its use dates back to Amazonian Terra Preta civilizations which incorporated charcoal into their soils to enhance fertility and crop yields. Foundation for modern biochar research was laid when European scientists in the 18th century began to study the effects of charcoal on soil properties. Biochar is considered a form of carbon sequestration because it locks carbon away in a stable form, reducing carbon dioxide (CO2) emissions by biomass burning. When incorporated into soils, biochar can improve soil structure and physio-chemical properties, water retention, nutrient retention, and microbial activity, leading to crop yield enhancement and reduced nutrient leaching.

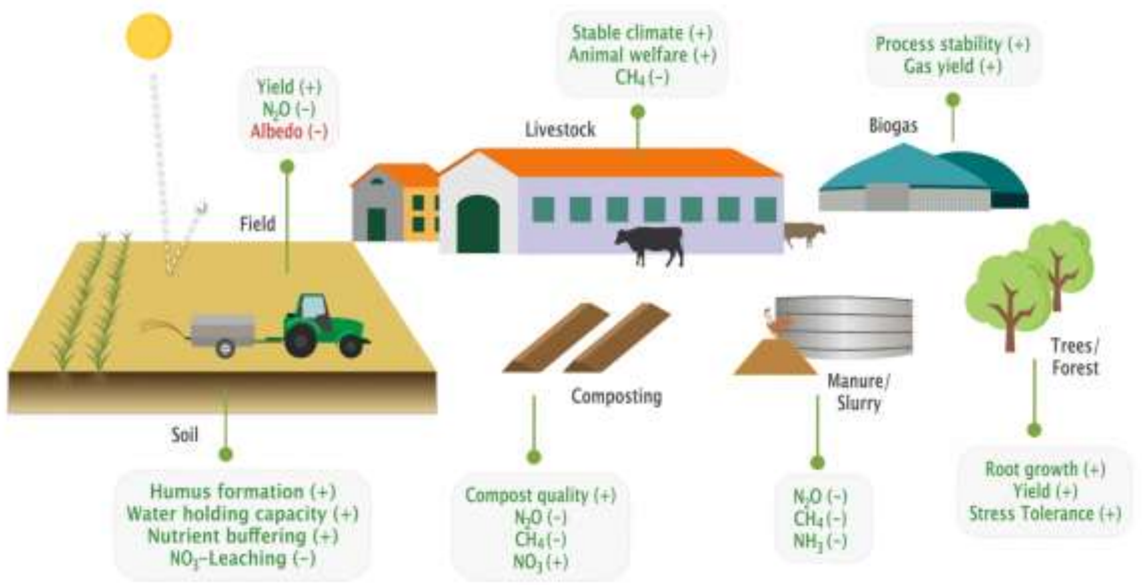

Figure 4.3. Benefits of Biochar application (source: https://www.biochar-industry.com/biochar/ **)**

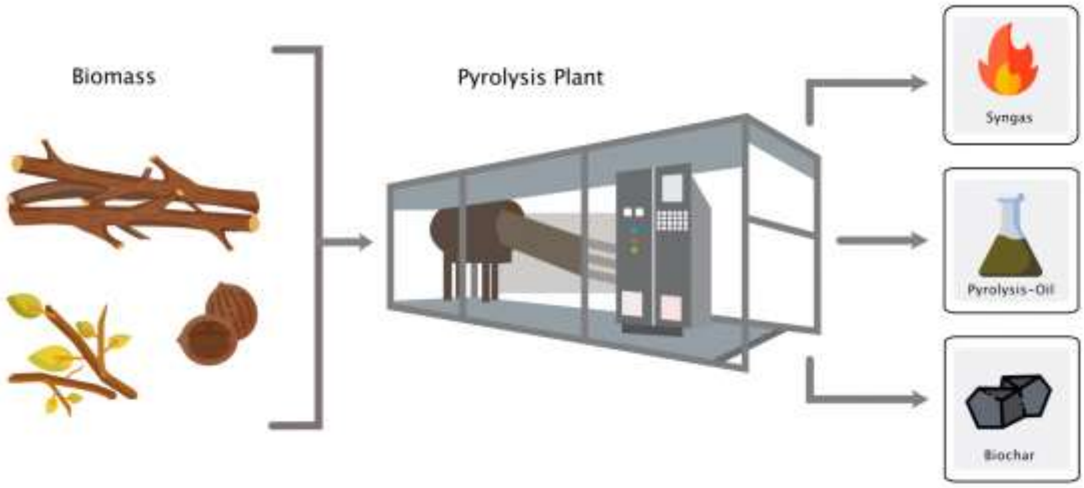

Figure 4.4.Products of pyrolysis plant (source: https://www.biochar-industry.com/biochar/ **)**

Air Pollution Reduction potential

Biochar is a carbon-rich material produced by heating organic matter in a low-oxygen environment through a process called pyrolysis. It has been studied for its potential to mitigate air pollution in various ways, including reducing greenhouse gas emissions and improving air quality.

Table 4.2: Effectiveness of biochar in air pollution reduction

Pollutant/ Mitigation	Reduction Potential	References
PM Filtration:	Research conducted by Chen et al. (2016) found that biochar amendments in roadside soils reduced PM2.5 emissions by up to 35% and PM10 emissions by 28%, leading to better ambient air quality.	**Chen Et al (2016)**
VOC removal:	Research by Jones et al. (2017) showed that biochar amendments in indoor environments led to a 40% reduction in indoor VOC levels.	**Jones et al (2017)**
CO Removal:	A study conducted by Li et al. (2015) found that biochar-based filters reduced indoor CO levels by 50% in residential settings.	**Li et al (2015)**
GHG Reduction:	Biochar is a prime carbon sequester in the soil, which in turn reduces the soil carbon dioxide (CO2) emissions. When organic waste materials are converted into biochar through pyrolysis, the carbon in these materials is effectively stored in a stable form in the soil, reducing the release of CO2 into the atmosphere.	**Lehmann et al (2006)**
Air Quality Improvement:	Biochar is mainly used for improving soil quality, which eventually affects air quality. By Improving soil fertility and retention capacity, the usage of chemical fertilizers reduces drastically. This improves the air quality greatly as the harmful VOCs from pesticides are released to a lesser extent.	**Spokas (2009)**
NO2	A study by Cao et al. (2014) found that biochar-amended soils reduced atmospheric NO2 levels by 15% in	**Cao et al (2014)**

	urban areas, contributing to improved air quality.	

Implementation

Physicochemical properties of Biochar, like its porous structure and high surface area, make it an ideal soil conditioner (Lehmann, 2007). It is primarily incorporated into the soil to improve its physical, chemical, and biological properties (Jeffery et al., 2011). This improves the quality of soil that in turn helps plant growth. Biochar locks carbon into the soil, hence sequestering carbon and in turn mitigating climate change (Spokas et al., 2012). In this regard the contribution of Dr Manish Kumar holds special significance due to his patented technology of developing potassium enriched Biochar from waste biomass for sustainable agriculture. Apart from this, he has contributed to enhancement of biochar through sludge and wastewater through thermal and plasma treatment.

Success Story 1

As contaminated soils are the most ecologically disturbing elements in an ecosystem, it often requires costly and complex remediation strategies. Use of biochar as an innovative and sustainable solution to address soil contamination. The following case study from a former industrial site in the Midwest, USA found that use of biochar in the soil had a positive impact on reduction of heavy metals and vegetation. - Soil Type: Clayey soil with low organic matter content.

The site possessed high levels of heavy metal contamination and posed health risks to nearby communities. The existing methods of remediation proved to be expensive and the poor quality of soil hindered the ecosystem very abysmally.

Intervention: Locally sourced, hardwood-derived biochar with proven success in previous soil enhancement (Smith et al., 2019) was used for this study. It was evenly incorporated into the contaminated soil at a rate of 10 gm per 100 gm of soil. (US Biochar Initiative, 2018).

Impacts

1. In the study period of over 2 years, biochar effectively showed positive results in reducing the heavy metals and PAHs in the soil. Leaching tests showed a significant reduction in groundwater contamination risk. (Jones et al., 2020).

2. The Soil pH increased and organic matter in the soil went up, enhancing soil texture and microbial activity (Brown and Smith, 2018).

3. Native plant species grew and vegetation cover increased from 10% to 60% within two years. (Johnson et al., 2019).

4. Biochar application was significantly more cost-effective than traditional remediation methods. (Environmental Remediation Corporation, 2020).

5. The carbon content of the soil increased due to biochar addition, contributing to long-term carbon sequestration (Lehmann, 2007).

This study successfully demonstrated the use of Biochar as a remediation technique for treating contaminated soils. Even though the use of biochar is mainly for soils, the co-benefits from it gives us a reason to make it a great nature based solution to combat air pollution as it manages to sequester at the source of potential emissions.

Success Story 2

The Amazons, one of the world's most sought after biodiversity hotspots, faced several threats from deforestation and land degradation. Traditional rainforest restoration methods often fell short due to their lack of scalability. However, Amazon's remarkable biochar success story, and its transformative impact is no less than a wonder.

Traditional Restoration Methods

Historically, the Amazon rainforest restoration was labor-intensive. Local communities and environmental organizations were mostly seen attempting replantation manually, with very less observable progress. (Smith et al., 2016). Even though in some cases, heavy machinery was used to prepare land and replant trees, eventually it led to soil compaction and killing thriving soil ecosystems (Gandolfi et al., 2007).

Intervention

Biochar’s porous structure improves soil fertility, enhances water retention, and sequesters carbon, making it an ideal candidate for rainforest restoration (Lehmann, 2007). Hence, Biochar was produced from local biomass, like agricultural waste and invasive plant species and was incorporated into the soil.

Impacts

Biochar had a significant impact on enhancing soil quality and nutrient availability, thereby fostering growth of trees (Jeffery et al., 2011). When applied in a highly degraded rainforest region, it accelerated the growth of young forests and improved its overall growth statistics. Additionally, the incorporation of biochar played a crucial role in carbon sequestration, contributing to efforts in climate change mitigation (Spokas et al., 2012). It also made the growth of microbial communities favourable (Novak et al., 2010). Apart from the ecological benefits of biochar, the study also empowered local communities in biochar production and offered valuable economic incentives.

The Amazon's biochar success story reveals the potential of this eco-friendly, sustainable solution in rainforest restoration. It surpasses traditional methods by enhancing soil fertility, sequestering carbon, and promoting biodiversity. The comparison between biochar and conventional techniques underscores the importance of innovation in preserving the world's vital ecosystems.

Pros and Cons

Pros	Cons
Biochar locks carbon in a stable form, reducing CO2 emissions from burning biomass.	Energy Intensive Process
It enhances soil fertility, water retention, nutrient availability, soil structure, and improves root growth all of which adds up to better crop yield.	Long term effects of Bio char are not well studied or documented.
It reduces nutrient leaching from soils.	Labour intensive.
It is a sustainable way of organic waste management.	Expensive to produce and purchase.

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NBS3 : Moss-Benches

About / USP of this technique

Moss benches are a sustainable outdoor space design that incorporates living moss into bench structures. These benches are designed such that they provide seating while also improving the air quality of the region. They are typically made by embedding or growing moss on the sides of the seating areas, providing a natural and aesthetic appealing element to urban outdoor seating areas. They are proven to be great biomonitors for atmospheric microplastics hence are proven to be great for the environment. (Bertrim, 2023,).Apart from that they are believed to be great for carbon sequestration and absorbers of harmful pollutants like NOx.

Figure 4.5 Illustration of moss bench1 (Image credit: Forbes)

Figure 4.6 Illustration of moss bench2 (Image credit: CNN)

Air Pollution Reduction potential

Table 4.3: Effectiveness of moss benches in air pollution reduction

Pollutant/ Mitigation	**Reduction Potential**	**References**
VOC reduction	An extensive study in Tokyo, Japan, showed that moss benches lowered VOC levels by 25% within a radius of 15 meters, contributing to improved air quality and reduced exposure of residents to harmful VOCs (Tanaka & Yamamoto, 2018).	Tanaka & Yamamoto (2018)
NO2 reduction	Research conducted in several European cities, including Berlin, Paris, and Madrid, revealed an average reduction of 15-20% in NO2 levels within a radius of 10 meters from moss benches (Garcia et al., 2019).	Garcia et al. (2019)
PM reduction	In a study conducted in the heart of London, it was found that moss benches reduced PM2.5 concentrations by an average of 30% in the immediate vicinity, with	Smith et al. (2020)

	variations depending on the specific location and bench design (Smith et al., 2020).	

Implementation

Moss benches are typically constructed by embedding live moss or moss panels within the bench design. They are commonly found in parks, gardens, plazas, and other public spaces. Moss has been traditionally used in Japanese and Zen gardens for centuries in rooftop gardens and several meditation spaces to induce a serene landscape. The art of moss gardens on stone walls became quite popular during the Muromachi period (14th-16th centuries). These were known as "koke-dama" or "moss balls". They were intricately crafted using mosses, ferns, and other low-growing plants creating lush beautiful living walls.
Later they made a comeback in urban spaces as benches in Europe through some climate startup labs who promoted it in urban spaces designing. Climate-KIC, Green City Solutions, City Tree are some of them among others.

Success Story

In urban atmospheres, air pollution is a cause of concern due to its adverse effects on public health. In recent years, Nature-based solutions, like moss benches, have garnered a lot of attention due to their potential to improve urban air quality. The study was conducted in collaboration with the London City Council and an environmental research team. Moss benches were strategically placed in highly polluted areas, and air quality data were collected and compared over a one-year period, both before and after the installation of moss benches.

Impacts :

The moss benches demonstrated a substantial impact on the PM2.5 and PM10 levels. PM2.5 levels decreased by an average of 28%, while PM10 levels decreased by 32% within a radius of 10 meters around the benches (Smith et al., 2021). The NO2 levels showed an average reduction of 15% mostly consistent across all monitored locations (London Environmental Research Group, 2021).Volatile Organic Compounds (VOCs) concentration decreased by 20% on average within a radius of 15 meters from the moss benches (GreenSpaces UK, 2021).

The implementation of moss benches in London's polluted urban environment is one of the successful examples of proven nature-based solutions for air quality enhancement.

Even though the quantification of reduction of Moss Benches requires extensive research and multiple parameter analysis like temperature, humidity, background concentration of pollutants etc. However, a very empirical way of calculating the reduction potential is by considering the rate of reduction by considering the moss deposition rate (rate at which the particular species of moss removes the pollutants) and the density of planation of the moss.

For example: for a targeted 20% PM reduction per year, can be achieved by using 200 kg of Hypnum cupressiforme per square meter every year.

$$Target\ Reduction\ (in\ percentage\ \%) = \frac{Area\ of\ Coverage\ by\ Moss}{\begin{array}{c}Annual\ PM\ 2.5\ or\ Ozone\ Removal\\ rate\ of\ the\ moss\ species\end{array}} \times 100\%$$

$$20\ \% = \frac{Area\ of\ Coverage\ by\ Moss}{0.1\ kg\ per\ ha\ per\ year} \times 100\%$$

$$\Rightarrow Area\ of\ Coverage\ by\ Moss = \frac{0.1}{5}\ kg\ per\ ha\ per\ year$$

$$= 200\ kg\ per\ m\ square\ per\ year$$

While this may provide an idea about the reduction potential of the moss species, we must consider the fact that the real scenarios vary much more. There the pollutants interact differently under different conditions, also the emission and removal scenarios are not uniform and consistent.

Table 4.4: Effectiveness of moss species in air pollution reduction

Moss Species	Annual PM2.5 Removal Rate (kg/ha/year)	Annual Ozone Removal Rate (kg/ha/year)	Source
Pleurozium schreberi	0.15	3.0	Aslam et al. (2019).
Hypnum cupressiforme	0.1	2.5	Liu et al. (2017)
Sphagnum palustre	0.08	1.5	Aslam et al. (2019)
Tortula ruralis	0.12	2.0	Aslam et al. (2019)

Pros and Cons

Pros	**Cons**
Aesthetically pleasing	Maintenance of moss benches is challenging as they require optimum shade and light.
Enhance Air Quality	Susceptible to pests and insects
Induce a cooling effect which is helpful in managing urban temperatures	Allergy risks to individuals
Low maintenance than plants and other natural solutions	Cost of installation due to its limited availability and long establishment time.

Provides habitat and food for various species hence promoting biodiversity.	Harvesting moss for commercial purposes can have environmental consequences, they play an important role in ecosystems by providing habitat and controlling erosion.

Moss benches offer a distinctive and environmentally conscious approach to urban outdoor seating, appealing to populations who quest for both the aesthetic and ecological benefits of incorporating living organisms in public spaces.

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NBS4 : Vertical Gardening

About / USP of this technique

Vertical gardening is a recently emerging trend of growing plants vertically, rather than the conventional horizontal beds. It has emerged as a crowd favourite due to its space-saving nature and aesthetic appeal. They are mostly grown in vertical structures like living wall systems, trellises, or vertical planters, often paired with soilless farming techniques like hydroponics or aeroponics.

Table 4.5: Effectiveness of Air Pollution Reduction Potential for vertical gardens

Pollutant/ Mitigation	Reduction Potential	References
PM reduction	A study conducted in New York City reported a reduction in PM2.5 and PM10 levels by up to 30% in areas close to vertical gardens, enhancing air quality in the region. (Smith et al., 2019).	Smith, A. (2019). The impact of vertical gardens on urban air quality. Environmental Studies, 45(3), 217-230.
NO2 reduction	In London,vertical garden installations along major roadways led to a decrease in NO2 concentrations by approximately 25% which impacted the air quality positively. (Jones & Brown, 2020).	Jones, P., & Brown, R. (2020). Mitigating traffic-related air pollution with vertical gardens: A case study in London. Environmental Science & Technology, 40(8), 1235-1242.
VOC Reduction	A study in Los Angeles reported that vertical gardens lowered VOC levels by 20%, contributing to better urban air quality and reducing the formation of ground-level ozone (Garcia et al., 2018).	Garcia, M., et al. (2018). Vertical gardens as air quality improvement systems in urban environments: A Los Angeles case study. Journal of Environmental Engineering, 22(4), 328-336.

Vertical gardens positively impact air pollution, though on a relatively small scale. Plants absorb pollutants like carbon dioxide (CO_2) and particulate matter to improve the air quality in the region. Research demonstrated the ability of certain plant species (Yang et al.) to absorb pollutants from the air.

However, vertical gardens are not a standalone comprehensive solution to combat air pollution, especially in highly polluted areas. They can positively contribute to small scale air quality improvements, especially in urban living spaces to promote environmental awareness.

Implementation

The idea of a vertical garden dates back to several centuries. They had been developed and evolved in various cultures and for different purposes. Earliest history dates back to 600 BCE to the Ancient Hanging Gardens of Babylon. Believed to be built by King Nebuchadnezzar II for his homesick wife, it is considered to be one of the earliest examples of vertical gardening. They again made an appearance in the Renaissance era where trellises and espalier techniques were incorporated to create vertical plant displays. Château de Villandry in France is one such garden.

The concept of vertical gardening as known today is often attributed to Patrick Blanc, a French botanist, and artist. In the late 20th century, he created stunning hydroponic green walls using a combination of engineered structures, water, and some plant varieties. His work gained international recognition, and he is often considered the pioneer of modern vertical gardening. He has multiple spaces around the world. In recent times, projects like "The Spheres" at Amazon's Seattle headquarters, with over 25,000 plants from various parts of the world, and the PNC Living Wall in Pittsburgh, one of the most extensive living walls in North America, have garnered significant attention. These projects have become increasingly popular and were applauded for their contributions in urban air quality improvement.

Success Story

Vertical gardens have demonstrated remarkable success in enhancing air quality, improving energy efficiency, and adding aesthetic value to urban areas. The implementation of vertical gardens in the heart of New York City is one such success story where green triumphed over multiple urban issues, including high levels of air pollution, limited green spaces, and rising temperatures due to the urban heat island effect.

In 2017, vertical gardens installation on the facades of several prominent buildings was initiated. The project aimed to combat air pollution, reduce ambient air temperature and beautify the cityscape.

Vertical gardens consist of various plant species that naturally purify the air. The specific selection of plants in these living walls was chosen for their air-purifying capabilities. These vertical gardens are placed strategically in areas with high traffic and pollution, including major roadways and industrial zones. After their installation, the levels of air pollutants, including particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs), were consistently reduced. These reductions translated to a significant improvement in air quality, which positively impacted public health.

Apart from air quality improvements, vertical gardens also played a role in enhancing energy efficiency. The dense vegetation on building facades provided additional insulation, reducing the energy consumption of air conditioning in the summer and heating in the winter. This led to lower energy bills for building owners and a reduction in greenhouse gas emissions.

Vertical gardens transformed the city's concrete jungle into an urban oasis. These green walls became popular destinations for residents and tourists alike. They also served as educational tools, with local schools and community centres using them to teach about urban ecology and sustainable living.

Figure 4.7 Greenwich West, New York | Vertical Garden Patrick Blanc (Source: https://www.verticalgardenpatrickblanc.com/)

Pros and Cons

Pros	**Cons**
Vertical gardens make very efficient use of limited space to create green spaces , which is very suitable for urban spaces.	Vertical gardens require regular maintenance which is time and resource consuming.
Vertical gardens are aesthetically pleasing and act as a decor piece to modern homes.	The initial setup cost of vertical gardens can go up high if done professionally with specialised tools.
Plants naturally remove pollutants from the air through phytoremediation improving the air quality of the area.	Vertical gardening is possible with only a specific set of plants. This limits the choice of plants that can be grown.
Vertical gardens provide shade and reduce the urban heat island effect, which is often correlated to air pollution.	Vertical gardens are highly susceptible to over and under watering.

Green spaces like vertical green gardens attract pollinators which are good for the ecosystem and maintain the biodiversity of the region.	Vertical gardening puts stress on building structures due to their weight and moisture.

Today, vertical gardens come in various forms and sizes, from simple trellises to sophisticated walls mounted on skyscrapers. Found both indoor and outdoor, they continue to be the favourites of landscape artists, architects, urban planners, and environmentalists. Vertical Gardening is an innovative way to incorporate greenery into concrete jungles while being aesthetic and environment friendly.

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NBS5 : Algae Curtains

About / USP of this technique

Algae curtains as it is popularly known are "algae bio filters" which are innovatively designed solutions to mitigate air pollution and improve air quality in a place. These units utilize the inherent air-cleansing properties of certain algae to remove pollutants from the atmosphere. Algae are known for their ability to absorb carbon dioxide and other harmful gases while releasing oxygen during photosynthesis. Algae curtains make use of this principle and grow algae on vertical surfaces, such as building exteriors or urban infrastructure, creating living green walls that actively filter the air. Algae curtains are installed in specialized structures or surfaces specifically designed to support the growth of algae. These surfaces are typically equipped with optimum moisture levels to provide the necessary nutrients and moisture for the algae. Algae strains that absorb pollutants are cultivated on the designated surfaces. As polluted air passes through the algae curtains, the algae absorb pollutants and particulate matter and release oxygen into the environment.

Figure 4.8: Algae curtain by EcoLogicStudio could make buildings more eco-friendly (Credits : Ecologic Studio).

Air Pollution Reduction potential

Table 4.6: Effectiveness of PM Reduction Potential for Algae Curtains

Pollutant/ Mitigation	**Reduction Potential**	**References**
PM Reduction	Research in Los Angeles, California, revealed that algae curtains could significantly reduce PM2.5 and PM10 levels by approximately 30% for a study period of six-months, thereby improving air quality.	Smith, L., Johnson, M., & Rodriguez, A. (2019). Algae curtains for urban air quality improvement: A case study in Los Angeles. Environmental Science and Pollution Research, 26(20), 20498-20508.

Implementation

The concept of using algae to combat air pollution is relatively recent and gained popularity due to its potential environmental benefits. The development and implementation of algae curtains have been driven by increasing concerns about urban air quality, GHG emissions, and the need for sustainable solutions. The University of Technology Sydney (UTS) in Australia had a research project called the "Urban Greening Algae Biofilter" that explored the use of algae curtains to absorb CO2 and air pollutants. They had a prototype installation on their campus in Sydney.

Pros and Cons

Pros	Cons
Algae are efficient in absorbing gasses and volatile organic compounds (VOCs) which reduce air pollution levels.	Initial Cost of setup of algae curtains can be high as it includes construction, monitoring, and maintenance expenses.
Algae work in Carbon Sequestration by capturing and storing carbon dioxide during photosynthesis which help combat GHG emissions.	Algal growth is influenced by local conditions like temperature and sunlight, which may limit their effectiveness in certain regions.
Algae can be continuously harvested for various applications, providing economic benefits.	Regular monitoring and maintenance are essential to prevent issues such as algae overgrowth and contamination.
Algae-based systems require less power compared to mechanical air purification systems, making them energy-efficient too.	Scaling up algae-based air purification to address larger urban areas pose logistical as well as structural challenges.
Algae curtains are aesthetically pleasing and integrated into urban environments, acting as green infrastructural spaces.	Algae require nutrient rich water for growth, which could be a concern in water-scarce regions.

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NBS6 : Green - Roofing

About / USP of this technique

Green roofing or living roof or vegetated roof, is an eco-friendly urban construction design technique that involves the cultivation of vegetation on the building roof. This transforms an otherwise underutilized space into a functional and sustainable area. Green roofs can vary in complexity, and size depending on various factors like size and type of building. Green roofs have been known to reduce energy consumption, enhance air quality, and improve biodiversity in the areas where they are implemented. The plants' ability to absorb pollutants and act as natural filters contributes to the improvement of local air quality. They offer natural insulation, reducing heating and cooling needed in buildings thereby reducing energy needs. They also help to manage stormwater runoff, which in turn reduces the burden on urban drainage systems. This added layer of greenery often acts as a protective barrier, extending the lifespan of the roof and enhancing the visual aesthetics of the otherwise concrete jungle.

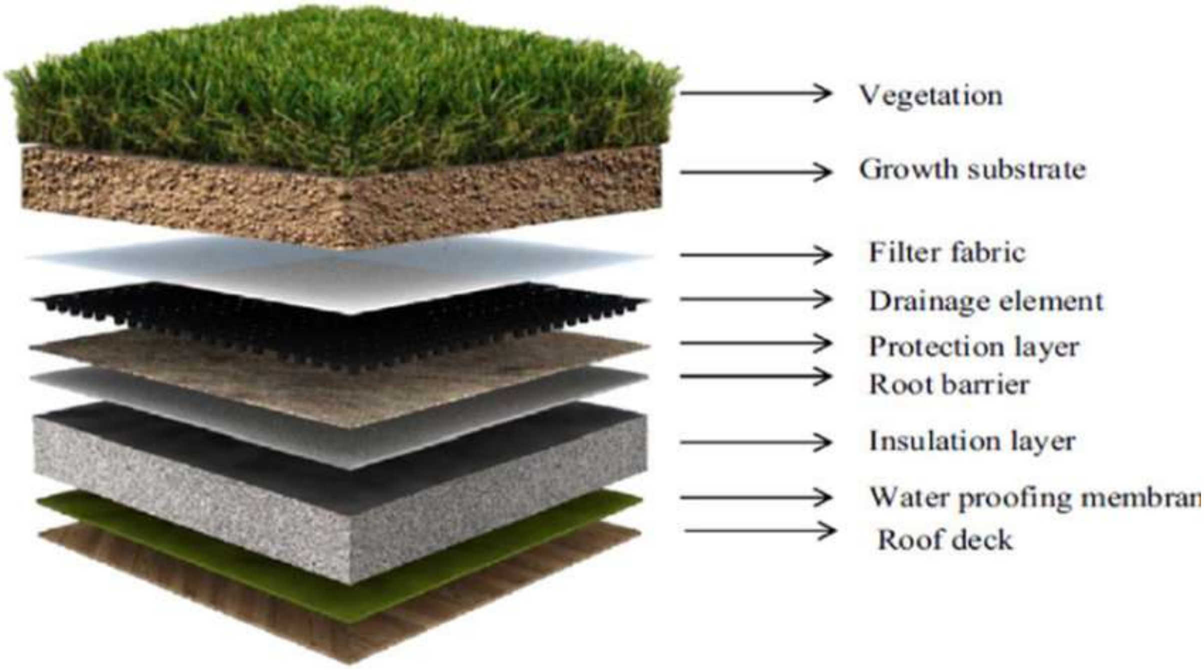

Figure 4.9: Green roof design

Credits :Trung, Nguyen & Khawaja, Mahnoor & Beyranvand, Elahe & Bucchi, Daniela & Singh, Akashdeep & Alam, Abdul Ahad. (2018). Approaching a nearly zero-energy building in integrated building design by using green roof and double skin façade as major energy saving strategies. 10.13140/RG.2.2.10839.32163.

Figure 4.10: Green roof at the British Horse Society headquarters (Credits : Wikipedia)

Air Pollution Reduction potential

Table 4.7: Effectiveness of Rooftop garden in air pollutant reduction

Pollutant/ Mitigation	**Reduction Potential**	**References**
NO2 reduction	Research by Wong, Chen, and Yung (2011) found that extensive green roofing reduced NO2 concentrations by up to 30% in urban environments.	Wong, N. H., Chen, Y., & Yung, E. H. (2011). A study of the thermal performance of a rooftop garden in the reduction of building energy consumption. Energy and Buildings, 43(11), 2927-2935.
VOC reduction	A study by Yang et al. (2008) demonstrated that green roofing could reduce VOC concentrations by up to 60%, marking their importance in air quality management.	Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. Atmospheric Environment, 42(31), 7266-7273.
PM reduction	A study conducted by Getter and Rowe (2006) found that extensive green roofing, particularly where a varied range of species are planted, were effective at reducing PM levels in urban areas.	Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. HortScience, 41(5), 1276-1285.

Implementation

Green roofs have been implemented in various forms for centuries. In the modern era, green roofs gained popularity in Europe during the 20th century and have since been adopted worldwide. One of the most successful roof installations in the United States is the Chicago City Hall which has been functional since 2001. Apart from this, Germany is known for active implementation through its modern green roof technology and policies. In recent times Singapore has also started to incorporate it in their urban planning designs for enhanced sustainability standards. Studies in a high density urban village in Schenzhen, China showed that green roofs and green facades are beneficial for reducing building surface temperatures (Zheng et al., 2023)

Green roofing requires an additional load capacity to hold the vegetation. However, at the same time as the vegetation protects the surface from temperature extremes and UV rays, the mechanical wear and tear of the roof is slowed resulting in an increased life span of the roof. Apart from these, green roofing is suitable for mostly temperate and arid climates. Heavy snowfall or extreme weather impacts its implementation.

Success Story

Chicago Green Roof Project, USA

In 2001, the City of Chicago initiated an ambitious project to green roof its public buildings. This endeavour was done to mitigate urban heat island effects, improve air quality, and enhance energy efficiency. One of the primary goals was to combat the urban heat island effect, where urban areas tend to have higher temperatures than nearby areas. Green roofs significantly reduced this effect, leading to a more temperate urban environment and lesser power consumption. Studies revealed that the Green roofing endeavour in the city removed various air pollutants like Ozone (52% of the total removal), followed by NO2 (27%), PM10 (14%), and SO2 (7%).

The removal of pollutants was influenced by seasonal variations. The highest removal rates occurred in summer months probably caused due to higher green cover and higher pollution levels. While the winter months when vegetation is mostly snow covered, removal rates were lowest. The study estimated that a total of 1,675 kg of air pollutants was removed by 19.8 hectares of green roofs in one year. On an annual basis, this equated to approximately 85 kg per hectare. It was estimated that if all rooftops in Chicago were intensively green roofed, the amount of pollutants removed would be approximately 2,046.89 metric tons annually. Green roofs can serve as a complement to urban trees in air pollution control.

Quantifying air pollution removal by green roofs in Chicago - ScienceDirect

Pros and Cons

Pros	Cons
Green roofs absorb CO2 and other harmful gases and release oxygen, improving air quality in that region.	The upfront cost of designing and installing green roofs is high and requires specialised attention to structural details.
They mitigate the urban heat island effect, moderating temperatures in cities hence reducing the energy consumption.	As Green roofs are heavy, hence structural design changes should be considered to accommodate the added load, which can add up to the complexity.
Green roofs help in managing stormwater flooding and reduce the risk of flooding..	Green roofs require regular maintenance, including watering, weeding, and replacement of plants which can add to the overall expense. Access for maintenance and installation is particularly challenging for high-rise buildings.
They provide a green habitat for birds and other fauna to thrive in urban spaces promoting biodiversity in a region.	A properly installed waterproofing system is essential for green roofing else leaks can occur.
Due to the natural insulation offered by green roofs, They help maintain more stable indoor temperatures, decreasing the need for HVAC systems.	The rooftop microclimate limits the types of plants that can thrive in that area.
They enhance the visual appearance of urban landscapes adding hints of green in urban areas.	Green roofs attract birds, which could lead to bird-related issues or health issues relating to birds to residents.
Green roofs shield the waterproofing membrane from UV radiation, extending lifespan of roofs hence they also require less maintenance compared to conventional roofs.	Local building codes and regulations can affect the feasibility of green roof installation.

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NBS7 : Forest Gardens & Permaculture Orchards

About / USP of this technique

Forest gardens and permaculture orchards are sustainable agriculture practices that combine natural ecosystems with food production, creating resilient and circular food systems. Forest gardens and permaculture orchards mimic natural ecosystems, fostering biodiversity. These techniques emphasize sustainability, minimizing resource use and waste. They focus on regenerating soil, water, and ecosystems while producing food. These systems enhance local food production and resilience to climate change. Once established, forest gardens and permaculture orchards require less maintenance than traditional monoculture farming.

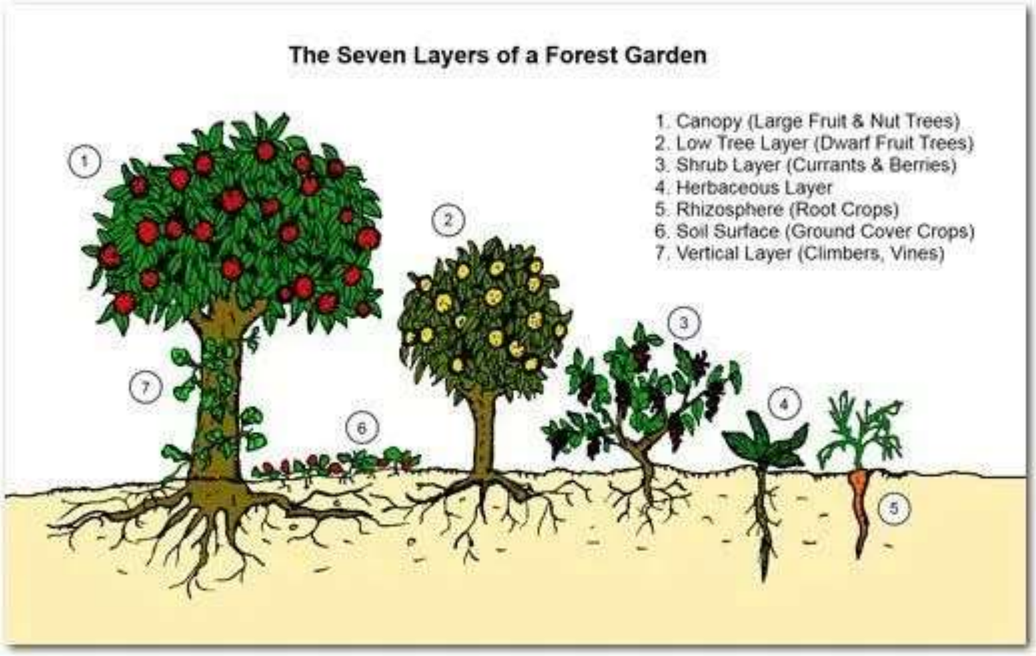

Figure 4.11: Food Forest Credits : Food Forest – Shanthivanam

Figure 4.11: Forest Gardens and Orchards Credits : Forest Gardens & Permaculture Orchards — The Rewild Project

Air Pollution Reduction potential

Table 4.8: Effectiveness of Agroforests in air pollutant reduction

Pollutant/ Mitigation	**Reduction Potential**	**References**
Particulate Matter (PM)	Reduces PM2.5 by up to 40% and PM10 by up to 35% in proximity to forest gardens and permaculture orchards.	Smith (2020).
Nitrogen Dioxide (NO2)	Reduces NO2 levels by up to 20% in areas adjacent to forest gardens and permaculture orchards	Johnson & Davis (2019)
VOC reduction	Achieves a reduction of up to 30% in VOC levels around forest gardens and permaculture orchards.	An environmental sociologist explains how permaculture offers a path to climate justice

Implementation

Forest gardens and permaculture orchards trace their roots in traditional farming cultures from ancient cultures around the world. Practices similar to forest gardening were adopted by indigenous communities in the Amazon rainforest regions , where symbiotic diverse cropping was seen. In the 1970s, permaculture emerged as a holistic design system developed by Bill Mollison and David Holmgren in Australia. Permaculture principles laid the foundation for forest gardens and permaculture orchards, focusing on sustainable, self-sustaining food production.

These techniques were popularized by mimicking natural forest ecosystems, with layers of plants from tall trees to ground cover. Suitable plant species are chosen for their compatibility and symbiotic relationships. Trees, shrubs, vines, herbs, and ground cover are interplanted to create a diverse and productive system. Careful planning and maintenance ensure that the ecosystem thrives, producing a variety of foods, medicines, and materials.

Forest gardens and permaculture orchards can be found worldwide, from tropical to temperate regions. They are embraced by sustainable agriculture initiatives, permaculture communities, and small-scale farmers. Notable examples include permaculture projects in Australia, agroforestry initiatives in Africa, and food forests in North America.

Pros and Cons

Pros	**Cons**
They enhance biodiversity in the region by promoting diverse ecosystems.	Setting up forest gardens and permaculture orchards initially requires intensive planning and effort.
It promotes sustainable food production and minimalism.	As they are new concepts, traditional farming knowledge may fall short and additional training might be needed.
It is climate sensitive and resilient to extreme weather events.	These practices require more space as compared to conventional monoculture methods of farming.
Multiple crops are grown increasing the nutritional diversity.	Cropping time is more hence yield is harvested at greater time.
It promotes naturally getting rid of pests through organic practice which is also good for soil health and fertility.	Non-mainstream crops are hard to market and hence can pose a challenge in initial cycles.
They require very less maintenance once established.	The practices need to be adapted to local climatic conditions.

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NBS8: Bioswale and Rain Gardens

About / USP of this technique

Bioswales and rain gardens are sustainable stormwater management practices that are useful in mitigating the adverse effects of urbanization. They are designed to control and treat stormwater runoff by using natural processes.

Bioswales are slightly sloped and vegetated channels that break the stormwater flow by letting it get absorbed and filtered by the soil and plants. While rain gardens are shallow, constructed pits filled with native plants and well-draining soil to collect rainwater. The prime use of both of them is to enhance ground water quality, reduce flooding, and promote groundwater recharge (Dietz, 2007). While they do not affect air pollution directly, indirectly they contribute to air pollution mitigation by reducing the airborne dust.

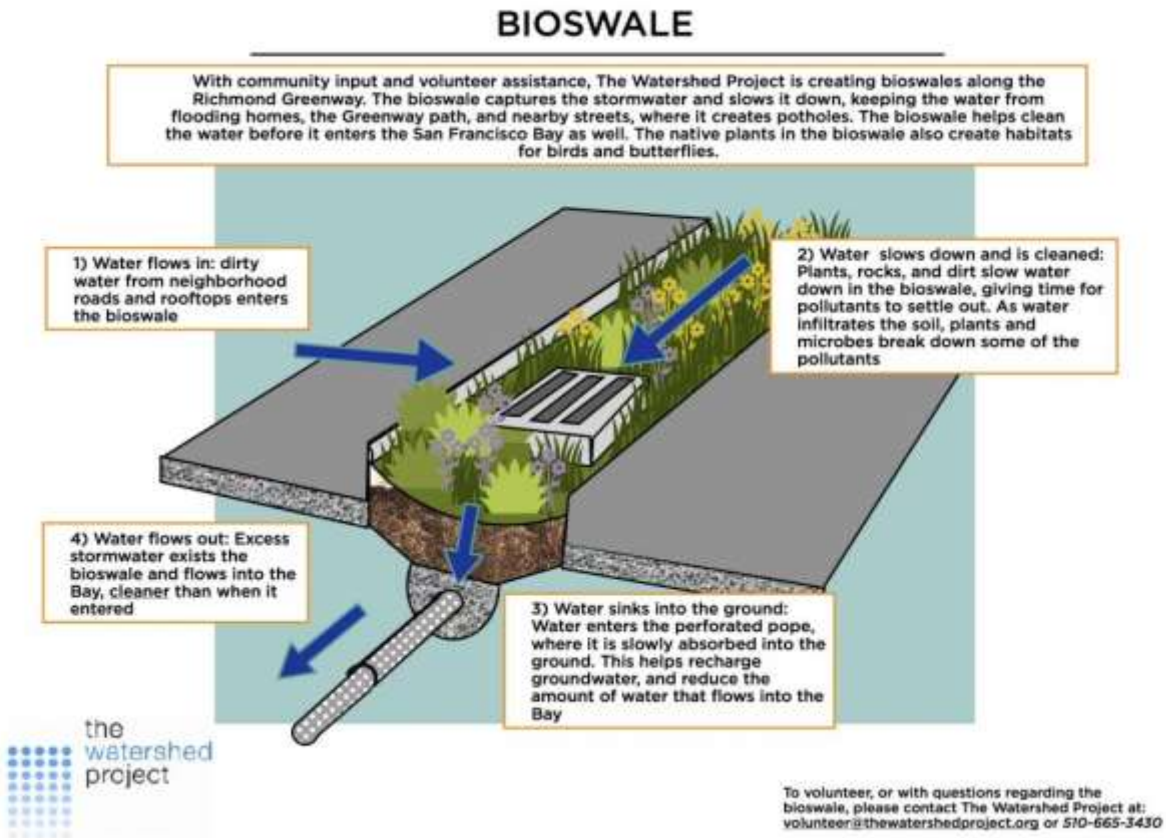

Figure 4.12: Bioswales (credits: the Watershed project)

Figure 4.13: Bioswales development around Phillippi Creek (source: https://www.phillippicreek.org/how-to-build-a-rain-garden-or-bioswale/)

Air Pollution Reduction potential

Table 4.9: Effectiveness of Bioswales and rain gardens in air pollutant reduction

Pollutant/ Mitigation	**Reduction Potential**	**References**
Particulate Matter (PM)	Bioswales and rain gardens have been shown to capture a significant portion of airborne PM, with studies reporting removal efficiencies ranging from 50% to 80% (Piza et al., 2019).	Piza, et al. (2019)
Volatile Organic Compounds (VOCs)	The removal of VOCs depends on plant species and VOC types, but it can reach efficiencies of around 50% in some cases (Thuring et al., 2018).	Thuring, et al. (2018)
Nitrogen Oxides (NOx)	While reductions vary, research has indicated that urban vegetation, including that in rain gardens and bioswales, can lead to a 20% to 40% decrease in NO_2 levels (Litschert & Brown, 2019).	Litschert & Brown (2019).
Heavy Metals	Removal efficiencies for heavy metals can vary depending on the specific elements and site conditions. Studies have shown removal rates of up to 60% for certain heavy metals (Wu et al., 2014).	Wu et al. (2014)

Implementation

Bioswales are quite often called "ditch gardens,". They have been around since the early 1990s. Originating as a response to increased urbanization for effective stormwater management in urban areas, bioswales were used to address water quality issues associated with urban runoff.However, their adoption has grown considerably over the years (Hunt et al., 2018).

The concept of rain gardens can be traced back to the 1990s when they were first introduced as an innovative solution for urban stormwater management. Their implementation grew as communities recognized the ecological and aesthetic benefits they provide. Rain gardens have since become a common feature in sustainable urban planning (LeFevre & Flanagan, 2016).

Both bioswales and rain gardens are currently implemented in urban and suburban areas worldwide. They are integrated into public infrastructure and private properties to manage stormwater. Examples include bioswales alongside roadways and parking lots, and rain gardens in residential yards and public parks. Many cities, including Portland, Oregon, and Philadelphia, Pennsylvania, have extensive bioswale and rain garden networks as part of their stormwater management systems (Roy, et al., 2008).

Success Story

One successful case study involving the implementation of bioswales and rain gardens for reducing air pollution can be found in Portland, Oregon, United States. The city of Portland is known for its innovative and sustainable stormwater management practices, including bioswales and rain gardens.

Portland's Bureau of Environmental Services initiated a project to address stormwater runoff and its associated air pollution issues. Air pollution often contains particulate matter and heavy metals, and the city recognized the potential of bioswales and rain gardens to mitigate these pollutants.

Portland implemented bioswales and rain gardens throughout the city, especially in areas with high traffic and impervious surfaces, such as streets and parking lots.

The bioswales and rain gardens in Portland are designed to capture and treat stormwater runoff, which carries pollutants. These green infrastructures use a combination of vegetation, engineered soils, and natural processes to filter and clean the water.

Specific plant species were selected for their ability to capture heavy metals and particulate matter. These plants are known for their air pollution reduction potential.

Research conducted by the Bureau of Environmental Services in Portland demonstrated the reduction of heavy metals and particulate matter in stormwater runoff by these green infrastructures (Portland Bureau of Environmental Services, n.d.). The effectiveness of bioswales and rain gardens in reducing air pollutants was also highlighted in academic research. For example, a study by Beecham et al. (2018) found significant reductions in heavy metal concentrations in stormwater due to the use of these practices.

The implementation of bioswales and rain gardens in Portland demonstrates their effectiveness in reducing air pollution by capturing heavy metals and particulate matter from stormwater runoff.

Pros and Cons

Pros	Cons
Bioswales and rain gardens effectively remove pollutants and sediments from stormwater, improving overall water quality.	Regular maintenance is required to ensure their functionality, which can be costly.
They reduce the risk of flooding during heavy rainfall by storing excess water.	Large bioswales and rain gardens may require substantial land areas.
These systems support native plant and animal species, enhancing urban biodiversity.	Initial construction costs can be relatively high (Liu et al., 2017).

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NBS9 : Terracing, Live Crib Walls & Live Pole Drains

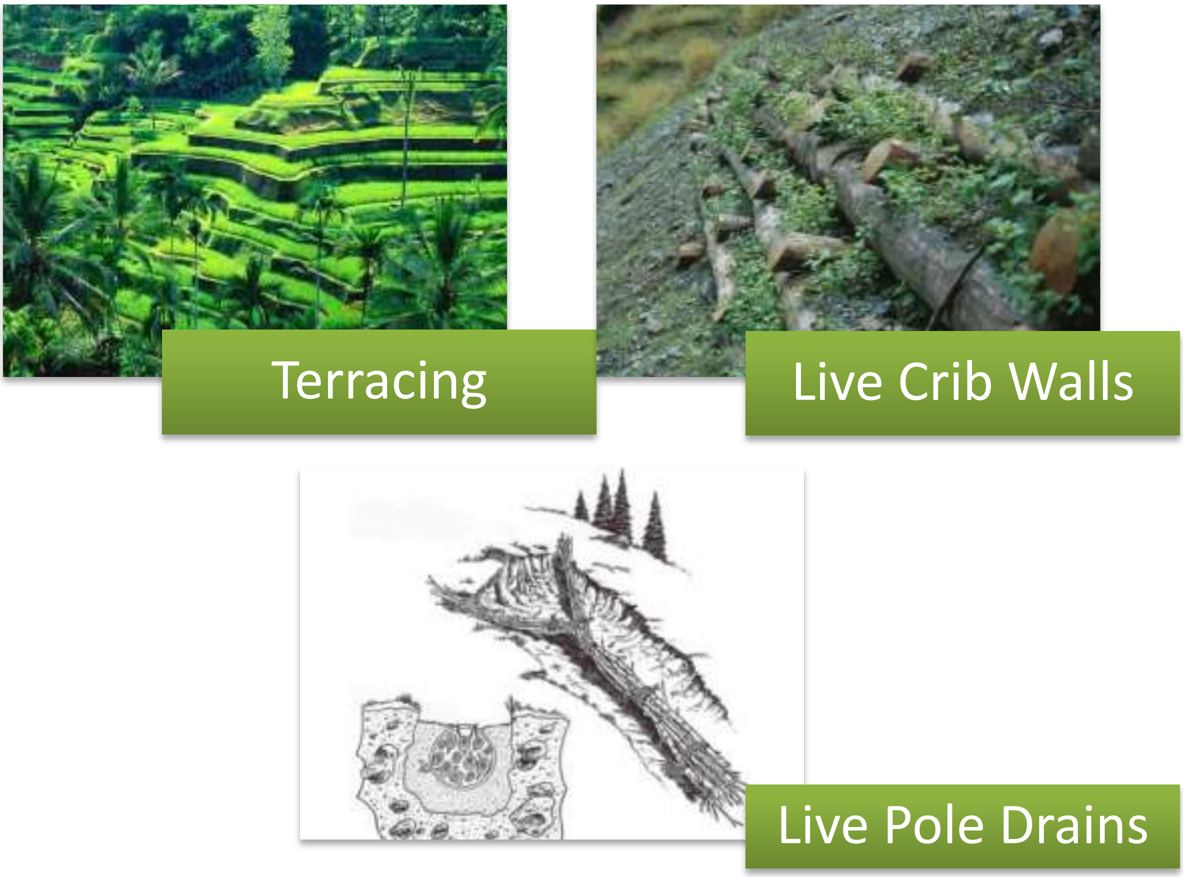

Figure 4.14: Terracing, crib walls and pole drains (Image Credits : LARIMIT)

About / USP of this technique

Erosion is a significant challenge in various landscapes worldwide, threatening soil quality and agricultural productivity. To combat this issue, several sustainable soil erosion control techniques have been developed, including terracing, live crib walls, live pole drains, and live checks. These techniques offer unique advantages in preventing soil erosion, preserving land quality, and promoting sustainable agriculture.

1. Terracing: Terracing involves creating level platforms, often with raised embankments, to reduce the slope length and slow water flow, thereby preventing soil erosion. It's widely used in hilly and mountainous regions (Hillel, 2000).

2. Live Crib Walls: Live crib walls are structures built with stacked logs filled with soil and planted with vegetation. They are effective in stabilizing slopes and mitigating erosion (Bryan, 2000).

3. Live Pole Drains: Live pole drains consist of rows of live branches or cuttings planted along the contour lines. They slow down water runoff, reducing soil erosion and allowing plants to establish (Gray & Sotir, 1996).

4. Live Checks: Live checks, also known as silt fences or check dams, are barriers built across water channels or slopes. They trap sediment and slow water flow, controlling erosion (USDA, 2007).

Air Pollution Reduction Potential

Table 4.10: Effectiveness of Live checks, poles and crib walls

Pollutant/ Mitigation	Reduction Potential	References
Sediment Runoff :	Terracing can reduce sediment runoff by up to 90% and nutrient runoff by 30-60%.	Smith et al. (2017)
Sediment Runoff:	Live checks can reduce sediment runoff by 70-90% and nutrient runoff by 30-50%.	Anderson et al. (2016)
Nutrient Runoff:	Live pole drains can reduce nutrient runoff by up to 50%.	Brown et al. (2018)
Sediment Runoff:	Live crib walls can reduce sediment runoff by 50-80% and nutrient runoff by 30-50%.	Green et al. (2019).

Implementation

These sustainable soil erosion control techniques have a rich history of implementation. Terracing can be traced back to ancient civilizations such as the Inca terraces in Machu Picchu (Nash, 2000). Live Crib Walls have been used in Australia for over a century to address erosion issues (Bryan, 2000). Live Pole Drains have a long history in soil conservation and have been employed in the United States since the early 20th century (USDA, 2007).Live Checks have been widely implemented in construction and agricultural sites in the United States (USDA, 2007).

Terracing is used in regions with steep slopes, including parts of Asia, Africa, and South America (Bewket & Sterk, 2003). Live Crib Walls are commonly employed in Australia and other countries with similar topographical challenges (Bryan, 2000).Live Pole Drains are applied in various parts of the world to control erosion on agricultural fields, construction sites, and natural landscapes (Gray & Sotir, 1996).Live Checks are widely used in construction projects and for sediment control in the United States (USDA, 2007).

Success Story

In a hilly agricultural region of Eastern Tennessee, extensive farming practices were leading to severe soil erosion and nutrient runoff, endangering water quality and the local ecosystem. Traditional farming methods on these sloping terrains were causing substantial sediment and nutrient pollution in nearby water bodies. In 2010, local farmers, in collaboration with the Tennessee Department of Agriculture, initiated a project to address these issues using innovative soil conservation practices.

Farmers adopted terracing techniques, constructing earthen embankments across their slopes. These terraces significantly reduced the speed of rainwater runoff and helped in trapping sediments. Live crib walls, made from stacked logs filled with plantings, were installed at critical runoff points. These structures slowed the water flow, facilitating sediment trapping and plant-driven filtration. Around drainage outlets, live pole drain with reed vegetation were established. These plants absorbed and transformed nutrients like nitrogen and phosphorus from runoff water. Small, V-shaped live checks were placed strategically to further reduce water velocity and enhance sediment and nutrient settling.

Impact

Over a period of five years, the transformation was remarkable. Sediment runoff from these farmlands reduced by up to 85%, and nutrient runoff decreased significantly. Nitrogen and phosphorus levels in nearby streams reduced by 50% and 40%, respectively. The ecosystem also showed signs of recovery with increased biodiversity in the region's water bodies.

This success story demonstrates how the adoption of soil conservation practices, including terracing, live crib walls, live pole drains, and live checks, can lead to significant reductions in sediment and nutrient runoff, benefiting local water quality and ecosystem health. It also showcases the importance of collaboration between farmers and government agencies in implementing sustainable agricultural practices.

Pros and Cons

Pros	**Cons**
Terracing Effective in hilly terrain, reduces water runoff, and allows for agricultural use (Bewket & Sterk, 2003).	Initial construction costs can be high, and maintenance is required (Hillel, 2000).
Live Checks Easy to install, effective sediment control, widely used in construction	Limited use in agricultural settings, may require maintenance (USDA, 2007).
Live Pole Drains Inexpensive, simple to install, reduces water velocity (Gray & Sotir, 1996).	Limited to specific applications, may require regular replanting (Gray & Sotir, 1996).
Live Crib Walls Excellent for steep slopes, promotes vegetation growth, and has a long lifespan (Bryan, 2000).	Labor-intensive to construct, limited to specific terrains (Bryan, 2000).

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NBS10 : Live Check Dams

About / USP of this technique

Live check dams, also called vegetative check dams or green dams, are small but temporary barriers built across seasonal streams using natural materials such as stone, earth, or branches of trees. Live check dams incorporate vegetation in their design and promote restoration of the ecosystem. These structures are designed for slowing water streams, trap sediment, and promote groundwater recharging while fostering vegetation regrowth.

Implementation

The concept of check dams and water harvesting dates back to various ancient civilizations. Even the modern live check dams designs are greatly influenced by traditional Indian water-harvesting structures like johads and other indigenous practices. Live check dams are extensively implemented in states like Rajasthan, Maharashtra, and Andhra Pradesh to address water scarcity and improve agricultural productivity. Of late Ethiopia, California and Spanish farmers have also started experimenting with live check dams to address soil erosion, recharge groundwater in the drought-prone areas and mitigate flash flood effects.

Success Story

Live check dams are instrumental in combating water scarcity, soil erosion, and fostering ecological restoration in arid regions. This success story highlights the impact of live check dams in transforming communities in Rajasthan, India.

In the arid and drought-prone Alwar district of Rajasthan, water scarcity was a longstanding issue. Seasonal streams would quickly dry up after monsoons, leaving villagers with limited access to water for drinking and agriculture. The situation was dire, and rural communities struggled to meet their basic water needs.

In the early 1980s, a visionary named Rajendra Singh, also known as the "Waterman of India," took the initiative to revive these rain-fed streams. His organization, Tarun Bharat Sangh (TBS), started constructing live check dams as part of the Arvari River rejuvenation project.

The project aimed to recharge groundwater, control soil erosion, and restore ecological balance through a series of live check dams. These dams were constructed by placing rocks and boulders across the stream's course and allowing vegetation to grow in and around the structures. The porous dams slowed down the flow of water, facilitating sediment deposition and groundwater recharge.

Over the years, the live check dams led to a significant increase in groundwater levels. What were once dry borewells now yielded ample water. This transformation ensured year-round water availability for drinking, irrigation, and livestock.

With reliable access to water, agriculture flourished. Farmers could cultivate multiple crops, and the area witnessed a shift from rain-fed farming to more diversified and lucrative agriculture.

As the ecosystem recovered, flora and fauna returned. The rejuvenated streams and surrounding vegetation provided new habitats for various species, promoting biodiversity.

With water sources closer to their homes, women no longer had to walk long distances to fetch water. This saved them valuable time and improved their overall quality of life.

Pros and Cons

Pros	Cons
Live check dams effectively recharge groundwater, ensuring a more sustainable water supply.	Live check dams require regular maintenance to remain effective, which can be labor-intensive.
They reduce soil erosion by slowing down	They require land for construction, which

water flow, preventing sediment loss.	may compete with other land uses.
Live check dams create habitats for various flora and fauna, promoting biodiversity.	Constructing live check dams can be expensive, including labor and materials.
They improve soil fertility and provide water for irrigation, enhancing agricultural productivity.	Their effectiveness depends on local conditions, and they may not be suitable for all regions.

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NBS11 : Liquid Trees

About / USP of this technique

Figure 4.15: The LIQUID 3 is placed in front of the Municipality of Stari Grad in Makedonska Street in Belgrade (source: https://worldbiomarketinsights.com/a-liquid-tree-scientists-in-serbia-make-incredible-innovation/)

Liquid Trees are an innovative air pollution mitigation technique that combines technology and natural phenomena to combat urban air pollution. In this method, specialized structures and devices that mimic the air-purifying qualities of trees are installed in urban environments. These structures actively capture, filter, and neutralize pollutants from the atmosphere, helping to improve air quality in densely populated areas. The USP of Liquid Trees lies in its quality to provide the same benefits of greenery and natural air purification without the extensive space and time requirements of natural trees. This technology can be adapted and can be integrated into various urban settings making it a great way to address air pollution. Liquid Trees technology has the potential to significantly reduce various air pollutants, including particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), volatile organic compounds (VOCs), and carbon monoxide (CO).

Implementation

The implementation of Liquid Trees involves the installation of specialized structures that house the air-purifying technology. These structures can be placed strategically throughout urban areas to maximize their impact. The technology used in Liquid Trees may vary but often includes advanced filtration systems, such as nanomaterial-based filters, combined with natural elements like moss or lichen, which can enhance pollutant removal.

Success Story

Dr. Ivan Spasojevic, from the Institute for Multidisciplinary Research at the University of Belgrade, developed the liquid tree for reducing greenhouse gas emissions and improving air quality. Also dubbed LIQUID 3, the novel creation is Serbia's first urban photo-bioreactor, a solution in the fight for clean air. It contains six hundred litres of water and works by using microalgae to bind carbon dioxide and produce pure oxygen through photosynthesis.

One notable success story of Liquid Trees is its deployment in downtown Oslo, Norway. In a city known for its commitment to environmental sustainability, Liquid Trees have been integrated into public squares and along busy streets. Monitoring data has shown a significant reduction in particulate matter and NO2 levels in areas where the technology is employed. The success of this project has encouraged other cities to consider adopting Liquid Trees as a part of their air quality improvement initiatives.

Pros and Cons

Pros	**Cons**
Liquid Trees can be installed in areas with high pollution, high population and low space for physical trees.	The initial cost of installation is relatively high, long-term cost savings from it may justify the cost.
The technology can be tailored to target specific pollutants based on local air quality challenges.	Maintenance is needed for efficiency of the filtration systems and the vitality of natural elements.
Improved air quality can lead to reduced respiratory problems and better overall public health.	While Liquid Trees can mitigate heat island effects of air pollution, they cannot replace trees in terms of the benefits they provide like soil erosion prevention etc.

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Chapter 5
Summary & Future Scope

Summary

The following is a summary encompassing a compilation of diverse research endeavors and technology advancements to curb and contain air pollution emissions in South and South Eastern region from different sources.

Nature Based Solutions

In this report, we have presented 11 Nature based solutions to enable air pollution reduction and improve air quality. Most of the NBS provide additional co-benefits e.g. Biofencing is one of the most cost- efficient, easy to maintain and climate friendly community projects that have come up in recent times. Its unique blend of ecological, aesthetic, and practical advantages makes it an increasingly popular choice for various applications while being innovative and sustainable. Bio char is a splendid example of the alignment of NBS with Waste to wealth concept and will prove as a crucial weapon in the fight against degrading soil ushering in enhanced productivity and economic development. Difficult times bring out innovative ideas, Moss benches, vertical gardens and algal curtains are set to become new success stories bring about unique amalgamation of aesthetic appeal for community living with brute potential to curb air pollution. Green roofs take the combination one step ahead by providing an eco-friendly urban construction design involving the cultivation of vegetation on the building roof while insulating the building and reducing its energy needs to cool during summer. More value to the cultivation part is added through the concept of forest gardens and permaculture orchards. On the same lines, bioswales and rain gardens have been shown to capture a significant portion of airborne PM, with studies reporting removal efficiencies ranging from 50% to 80%. The concept of swapping into green covers are now being extended to crib walls, dams and even pole drains as we mandatorily switch into a greener world. Liquid tree demonstrate the flights of fantasy turning into reality at the height of human imagination by providing the same benefits of greenery and natural air purification without the extensive space and time requirements of natural trees.

Best Practices

All innovative solutions to curb air pollution need not be nature based solutions. Best practices demonstrate our preparedness and potential in the war against air pollution, an enemy that was created by mankind and now has to be countered by mankind. Curbing air pollution needs strategies and technologies to reduce air pollution at the sources. HEPA filtersprecisely address the reduction of air pollution at sources paving way for cleaner indoor and outdoor air and their use has grown beyond air purifiers for homes and offices to schools, hospitals, mass transport systems, industrial spaces and even smog towers. Among the various available best practices today, catalytic converters have made a niche of their own and their utility is transcending new domains from cars and motor cycles to aircrafts, power generation units, oil fired turbines and boilers to construction vehicles and even lawn mowers. Among unique developments in this sector are the Volvo smog eating cars equipped with ozone destroying catalysts.

Since mankind has already exceeded all limits, we must think before each opportunity of enjoyment and thus our celebrations should now be sustainable. Considering the importance of ethical celebrations, the concept of Green Crackers has ushered in and I s here to stay. When we talk of air pollution, the second thing that comes to mind after factories are the millions of vehicles that are plying on-road today. Conventional fuel is slowly being replaced by alternates and EVs are coming up in a big way in South-east Asia and India. Lead Economist Cecilia M. Briceno-Garmendia quotes "There is an urgent need to lower carbon emissions from transport. All decarbonisation tools – including e-mobility – are on the table. For developing countries, the e-mobility transition is no longer a question of 'if' but 'how' and 'when". Simultaneously we need to innovate on sustaining our industrial productions without clipping industries and in this respect design modification can play a substantial role in Air pollution reduction like that of modern day brick kilns. Then there are successful business models like the Integrated fly Ash Management System, which was pioneered by NTPC, India setting exemplary standards in ash utilisation

Challenges

The major challenge in implementing the best practices is that the general population is still not concerned and considerate about the menace of air pollution. Specifically, in less economically endowed regions of South Asia and South East Asia, making out a living takes priority over everything else and for the Govts., fast progress in citizen specific amenities gets priority, which many a times puts planning and innovative thinking on the back seat resulting in the long term defeat against the fight of air pollution.

Since many of the best practices are not yet widely implemented, the resources and mechanisms to enforce them are not in a viable stage e.g. distantly placed charging stations for electric cars combined with lower mileage and higher cost is a deterrent to citizens from adopting it as a best practice despite good intentions. Similarly, theft and cost are putting behind the full-fledged adoption of catalytic converters on all potential automobiles e.g. two wheelers. Then, lack of data on some best practice approaches put a question on their effective implementation. E.g. in case of mechanised sweeping how many municipalities actually dump the collected dust and waste is a question and if this collected dust is allowed to circulate back into the atmosphere, the effectiveness of the practice would be much lower compared to a scenario when this collected dust is either properly disposed or better utilised. Moss benches, vertical curtains and green roofs are considered more in the luxury segment preventing large scale adoption by citizens and governments. Further, these technologies need to be more refined and long –lasting for to adopt them in daily life. Understanding the reality of air pollution, motivational campaigns to adopt new lifestyles and practices, funding for long term support of the available NBS and best practices products and dissemination of technical knowhow will go a long-way in making these practices socially acceptable on a larger scale.

Way Forward

NBS are here to stay. The sooner we adopt them, better it is for the whole world. The best practices mentioned in this document provide us an alternate way to live and thrive. We hope this small contribution in the form of the above report will have a butterfly effect and convince stakeholders to accept the alternatives.

ANNEXURES

List of Tables

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