4. SUSTAINABLE DEVELOPMENT THROUGH ENERGY TRANSITION & DECARBONISATION PATHWAYS

Addressing energy transitions, decentralized systems, and low-carbon technologies.

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Chapter 2:
Resilient Healthcare through Energy Access: A Decentralised Pathway for Sub-Saharan Africa

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Executive Summary

The provision of quality healthcare in Sub-Saharan Africa (SSA) is critically undermined by inadequate access to reliable electricity. According to the World Health Organisation (WHO) (2023), nearly 60% of health facilities in the region lack dependable power, 15% are completely unelectrified, while 45% function with only intermittent or unstable electricity. This severely compromises essential medical services such as vaccine storage, maternal and emergency care, and diagnostic procedures. The COVID-19 pandemic further exposed these vulnerabilities, particularly in cold chain logistics and emergency responsiveness.

This thesis explores Decentralised Renewable Energy (DRE) technologies, primarily solar mini-grids and hybrid systems, as sustainable and context-appropriate solutions to address energy deficits in healthcare infrastructure. Evidence from case studies in Nigeria and Uganda reveals that solar mini grids can reduce carbon emissions by over 50%, deliver up to 95% electricity uptime, and enhance rural healthcare accessibility by approximately 35% (Moner-Girona et al., 2021).

Positioned at the intersection of public health and energy security, this research examines the viability of decentralised energy models for healthcare electrification. It draws on data from leading global institutions such as WHO, Sustainable Energy for All (SEforALL), and IRENA to analyse operational success stories, implementation barriers, and critical policy gaps. The findings demonstrate that solar-based systems not only enhance energy reliability but also reduce dependence on costly, polluting diesel generators. However, widespread deployment is impeded by fragmented policies, limited financing, and inadequate maintenance infrastructure. These systemic challenges necessitate urgent and integrated action.

Context and Problem Statement

Electrifying healthcare facilities in Sub-Saharan Africa should be recognised as a fundamental component of public health strategy, rather than a secondary development objective. The deployment of decentralised renewable energy systems such as solar mini grids must be supported through coherent policy frameworks, sustained financial investment, and local capacity development. Achieving Sustainable Development Goals (SDG 3: Good Health and Well-being and SDG 7: Affordable and Clean Energy) depends on ensuring that reliable electricity is an integral element of healthcare infrastructure. Without it, the delivery of effective and equitable healthcare cannot be realised.

Literature Review

Sub-Saharan Africa's healthcare systems face a chronic infrastructure gap, with energy poverty being among the most pressing and under-addressed challenges. Electricity is essential for powering lifesaving equipment, ensuring 24/7 care, maintaining vaccine cold chains, and supporting digital health systems. Yet over 60% of healthcare facilities in SSA operate without reliable power.

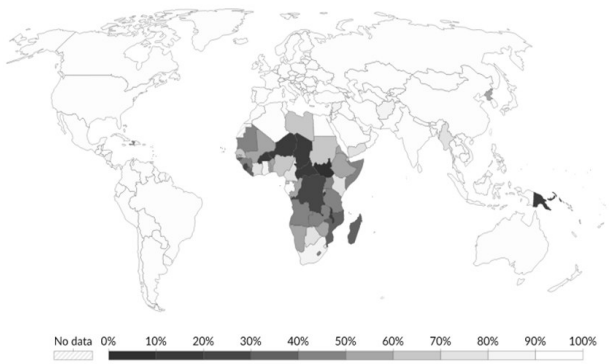


Figure 1: Share of the population with access to electricity, 2022 (World Bank, 2022). Having access to electricity is defined in international statistics as having energy sources that can provide basic lighting, and charge a phone, or power a radio for 4 hours per day.

A WHO report (2023) reveals that 15% of these facilities are entirely un-electrified, mostly in rural and peri-urban areas. Power outages or the absence of electricity severely limits healthcare delivery. Nighttime operations, maternal deliveries, and emergency care become risk-laden or impossible. Without consistent power, healthcare professionals cannot operate basic diagnostic equipment or preserve heat-sensitive medicines, which results in higher mortality and morbidity rates. The problem is further exacerbated by climate change, increasing disease burdens, and economic instability.



Figure 2.1: SSA data for Healthcare electricity (Source: SEforALL)

Although initiatives like WHO's *Energy for Health*, SEforALL's *Powering Healthcare*, and donor-driven electrification pilots exist, implementation remains sporadic. Projects often fail due to a lack of long-term maintenance planning, insufficient training for health workers, and fragmented institutional responsibility.

Additionally, energy interventions are typically donor-driven and focus solely on infrastructure, overlooking critical elements like operational training, maintenance funding, and local community engagement. In many cases, even when solar systems are installed, they are left unused due to minor technical issues and the absence of trained staff.

The core gap is not technological but systemic: insufficient coordination between health and energy sectors, lack of coherent policies, and poor integration of electrification into national health plans. This thesis seeks to address these systemic gaps by proposing context-specific, sustainable, and scalable electrification strategies tailored to SSA's healthcare sector.

Energy access and healthcare are increasingly recognised as interlinked development priorities. Literature by Adair-Rohani et al. (2013) and WHO (2023) highlights that healthcare facilities lacking electricity are significantly less effective in providing essential services such as childbirth, vaccinations, and surgery. The literature makes a compelling case for energy as a social determinant of health. SEforALL's *Powering Healthcare* report (2021) identifies DRE solutions, particularly solar

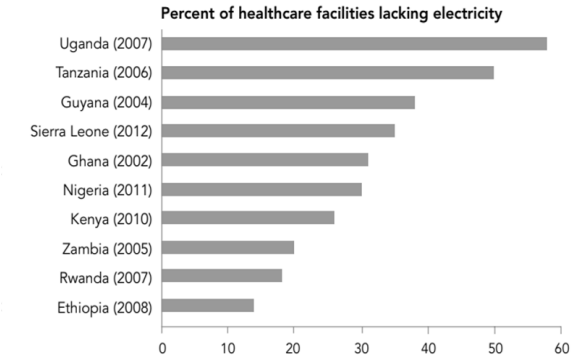


Figure 2.2: High Electricity deficits for healthcare facilities (Adair-Rohani et al., 2013)

PV and hybrid mini grids, as key to achieving universal energy access in healthcare facilities. These technologies offer reliability, cost-effectiveness, and climate resilience, particularly in off-grid and under-electrified areas.

Bhattacharyya (2013) and Cross & Murray (2018) explore the practical and institutional challenges of implementing decentralised energy systems. They emphasise the need for local capacity building and community ownership for long-term sustainability. Other scholars critique the "infrastructure-only"

approach, pointing out that electrification must be integrated into health system planning and workforce development.

Despite a growing body of evidence, the literature also shows significant gaps. There is limited work on gendered impacts of energy-poor health systems or on mechanisms for integrating energy access into public health policy. Moreover, many studies treat electrification as a stand-alone technical intervention rather than as part of a holistic healthcare delivery model. This thesis builds on and contributes to this body of work by focusing on policy frameworks, stakeholder engagement, and sustainability planning. It advances the argument that electrification must be embedded within health system strengthening efforts and aligned with national development goals.

Research Focus

Research Questions

1. How does a lack of reliable electricity affect healthcare delivery in SSA?
2. What decentralised renewable energy models are most effective for rural and semi-urban healthcare electrification?
3. What policy frameworks are required to scale these models?

Objectives

1. Assess the current energy access status in SSA's healthcare sector
2. Evaluate solar-based decentralised energy models for viability and sustainability
3. Identify policy gaps and propose actionable recommendations

Methodology

This study employs a mixed-methods research design to comprehensively investigate the current status, challenges, and opportunities in electrifying healthcare facilities in SSA. By integrating quantitative data with qualitative insights, the methodology provides both a macro-level overview and a detailed understanding of localised implementation, making it well-suited for analysing the multidimensional links between energy access and healthcare delivery.

Quantitative Component: Measuring Energy Gaps and Health Outcomes

The quantitative aspect of the study focuses on assessing the extent and reliability of electricity access in SSA's healthcare sector and evaluating the performance and sustainability of DRE systems. Secondary data will be sourced from established institutions such as WHO (SEforALL), the International Energy Agency (IEA), the World Bank, and national ministries of health and energy.

Key indicators to be analysed include the percentage of healthcare facilities connected to the national grid, those relying on diesel generators, and those entirely un-electrified. Additional metrics include outage frequency and duration, disruptions in service delivery, and critical health outcomes such as maternal mortality, emergency response efficiency, and vaccine storage failures. Descriptive statistics and time-series analysis will be used to identify trends and patterns. Furthermore, Geographic Information System (GIS) tools like QGIS and ArcGIS will support spatial mapping of electrified versus non-electrified facilities, revealing regional disparities and clusters of energy-deficient health infrastructure.

Qualitative Component: Understanding Impact and Implementation

The qualitative component seeks to explore how energy access affects healthcare delivery, identify successful DRE implementation models, and examine policy and institutional barriers. Case studies will be conducted in Nigeria and Uganda, selected for their contrasting energy contexts and ongoing healthcare electrification efforts. The focus will be on rural and semi-urban facilities that have adopted solar mini grids within the last three to five years.

Data will be gathered through semi-structured interviews with policymakers, energy service providers, healthcare workers especially those in maternal care and relevant NGO and donor representatives. Focus group discussions with patients and local community members will offer additional perspectives on perceived changes in service quality and accessibility. A SWOT analysis will be applied to each case

study to evaluate factors such as policy coherence, financial sustainability, maintenance practices, and stakeholder involvement.

Triangulation and Integration of Methods

To enhance the validity and richness of the findings, the study integrates data from both quantitative and qualitative sources. This triangulated approach allows for cross-validation of results and a deeper understanding of context-specific innovations and implementation challenges.

Matrix frameworks will be used to compare patterns across countries, facility types, and stakeholder groups, while narrative synthesis will help merge statistical data with qualitative observations, highlighting common themes and divergences.

Sampling Strategy

A purposive sampling strategy will be used to select healthcare facilities and stakeholders. Facilities must have implemented decentralised electrification within the past three to five years. The sample will include both primary healthcare centres (PHCs) and district hospitals, ensuring diversity in service level and geographical context.

Special attention will be given to gender representation and inclusion of stakeholders across the energy and health sectors. This comprehensive approach aims to generate actionable insights and inform a practical policy roadmap for healthcare electrification in SSA.

Key Findings and Argument

This study reveals a series of interrelated findings that collectively demonstrate the critical role of energy access in strengthening healthcare delivery in Sub-Saharan Africa. Through a combination of quantitative data analysis and qualitative case studies, five major themes emerged, each highlighting distinct but interconnected aspects of the energy-healthcare nexus. Together, these findings substantiate the argument that decentralized renewable energy solutions, particularly solar mini grids, are not only technically viable but also essential for delivering equitable and resilient healthcare in the region.

Theme 1: Energy Access Directly Correlates with Health Outcomes: Facilities with uninterrupted solar power reported improved maternal health services, better vaccine storage, and higher patient satisfaction. In Nigeria, a pilot solar mini-grid project led to a 60% increase in nighttime emergency services within the first six months.

Theme 2: Solar Mini-Grids are technically and economically feasible: Solar mini grids combined with battery storage and backup generators provided >95% uptime. Lifecycle costs were 30–40% lower than diesel-based systems. Environmental impact was also significantly reduced, supporting SDG 13.

Theme 3: Institutional Fragmentation is a Key Barrier: Policies regarding energy and health often operate in silos. Ministries lack coordination, leading to poor resource allocation and project duplication. In Uganda, delays in electrification were linked to unclear jurisdiction between national health and rural electrification agencies.

Theme 4: Long-Term Maintenance and Training Are Overlooked: Many solar systems failed within 2–3 years due to the absence of local technicians or spare parts. Training health workers on system usage was rare, despite its criticality for operational sustainability.

Theme 5: Gendered Impact of Electrification: Female health workers reported feeling safer during nighttime duties in electrified clinics. Mothers preferred delivering in facilities with lights and working equipment, contributing to increased institutional births.

Conclusion of Argument:

Electrification must be reframed not as an infrastructure project, but as a core health intervention. Decentralised solutions, especially solar mini grids, are scalable, sustainable, and contextually appropriate for SSA. However, success hinges on integrated policies, community involvement, and sustainable financing.

Policy & Practice Implications

Integrate Electrification into National Health Planning: Healthcare electrification must be formally embedded in national health sector plans. Ministries of Health and Energy should establish joint task forces to coordinate implementation, monitor outcomes, and allocate budgets collaboratively.

Promote Scalable Financing Models: Introduce results-based financing and public-private partnership models to attract investment. Donor agencies should fund not just capital expenditure but also maintenance, training, and local capacity building.

Establish Maintenance and Training Ecosystems: Every healthcare electrification project should include long-term O&M contracts with local technicians. Training health staff in basic troubleshooting and energy management is crucial for system sustainability.

Localise Energy Planning and Encourage Innovation: Leverage community-based organisations and local governments to co-design energy solutions. Innovations such as energy-as-a-service (EaaS) models, pay-as-you-go solar, and blockchain -based energy tracking should be piloted and scaled. These recommendations align with SDG 3 and SDG 7 while contributing to SDG 13 (climate action) and SDG 5 (gender equality), making them both practical and ethically grounded.

Conclusion

This study reaffirms that access to reliable electricity is an indispensable component of effective and equitable healthcare delivery in Sub-Saharan Africa. Across the region, persistent power deficits continue to compromise health outcomes, hinder service delivery, and strain healthcare systems, particularly in rural and underserved areas.

The research demonstrates that decentralised renewable energy solutions, most notably solar mini grids, can play a transformative role in addressing these challenges. When implemented with appropriate technical design, long-term maintenance strategies, and inclusive policy frameworks, these systems substantially enhance the reliability of essential services such as maternal care, emergency response, and vaccine storage.

By reconceptualising energy access as a public health imperative rather than a standalone infrastructure goal, this paper advocates for a paradigm shift in healthcare and energy policy planning. Cross-sectoral collaboration among national governments, international donors, energy providers, and local communities is vital to scaling up sustainable and resilient electrification initiatives. Moreover, integrating energy access into the core of health system strengthening efforts will contribute meaningfully to the achievement of Sustainable Development Goals 3 (Good Health and Well-being) and 7 (Affordable and Clean Energy).

Future research should build on these findings by exploring diverse implementation models, innovative financing mechanisms, and community-driven maintenance frameworks. Only through such a holistic, inclusive, and sustainable approach can healthcare facilities in Sub-Saharan Africa become resilient to both public health crises and broader environmental and economic disruptions.

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7. Pathways for Decarbonization: Strategies for Achieving Net-Zero Emissions in Energy-Intensive Industries

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Executive Summary

In order to prevent escalating climate change, reducing emissions from different industrial sectors is necessary. The emissions of greenhouse gases from various sectors have led to long-term increase in the earth's global temperature. This global warming has disastrous effects, such as frequent cloudbursts, cyclones, floods, and droughts especially in topographically sensitive zones. Implementing decarbonization pathways in the different sectors particularly in transportation, residential, and commercial, is indispensable to achieve climate mitigation and the net zero strategies [1]. Among these sectors, industries contribute one-third of total greenhouse gas emissions. Several industrial processes such as iron & steel making, cement manufacturing, production of fertilizers, and petrochemicals emit many greenhouse gases. In industries, an enormous amount of energy is required across various industrial processes. Coal is the primary fossil fuel that contributes significantly to greenhouse emissions.

Critical factors that affect industrial emissions are (i) the presence of large no. of small-scale industries, (ii) unplanned industrial growth, (iii) lack of policy to control emissions, (iv) use of outdated technology, and (v) lack of policy to control the emissions. Decarbonizing the industrial sector is essential because it is fundamental for developing low-carbon technologies such as energy-efficient buildings, renewable electricity, and generation. Identify the applicable funding agency here. Different technology, operational choices, and product design choices can reduce greenhouse emissions and energy consumption faster. The use of circular economy interventions, i.e., product longevity, reusability, ease of refurbishment, and recyclability, can reduce emissions in industrial sectors. Increasing energy demand has created a burden on fossil fuel consumption, leading to a drastic increase in the rate of carbon emissions [2]. The GHG emissions are rising at an intense pace. In developing countries, industries are the primary source of emissions, with coal as its primary fossil fuel. It is responsible for around 50 % of all GHG emissions, followed by manufacturing and construction (22%), transportation (11%), and industries (5%). Several technologies, decisions in product design, and operational strategies may quickly and affordably reduce energy use and GHG emissions across many businesses [3]. While still offering the same or better services, methods like lightweighting and design for longevity/reuse offer strategies to reduce material use. The image includes more than just technologies. By enacting the appropriate rules, investments in cleaner industrial processes can become more viable, and emission reductions can be accelerated significantly. The proper authorities can disseminate ideas through global supply chains, boosting businesses in nations without robust domestic regulations [4]. Cement production, oil refineries, and iron and steel production contribute to around 7%, 6%, and 5% of the 20–30% of emissions from industrial sources.

This position paper argues that current governance mechanisms are inadequate to address the specific wastewater challenges faced by India's small towns. It recommends urgent investment in decentralised wastewater treatment units (DWWTs), the establishment of town-level river health governance bodies, and the institutionalisation of water quality modelling in local planning frameworks.

Context & Problem Statement

Decarbonizing of the industry is one of the key issues in the modern, developing world. Although it can be challenging to comprehend, it dramatically impacts life and business operations. From a sustainability perspective, knowing the potential weaknesses will help businesses decide how to effectively engage in industrial CO2 removal. Industries contribute significantly to total emissions. Several industrial processes such as cement production, iron and steel making, and chemicals release a huge quantity of greenhouse gasses [5]. Several techniques are used to decarbonize industries across the supply and demand sides as shown in Fig 1.

A. Demand side technologies

Demand side techniques include extended product life, increased product usage driven by changes in demand, material substitution, and efficiency through circular economy initiatives.

1) Circular Economy: The concept of a ”Circular Economy” (CE) has emerged. Products at the end of their proper life cycle are considered resources in a CE. CE is not just one thing (like ”recycling”) but rather a series of solutions that maximize the value of every product, component, and material by using them as effectively as possible [6]. The first purchaser to keep using the product for as long as possible, to pass it on to other people, and take care of it so that it lasts as long as possible before needing replacement or repair [7]. In cases where this is not an option, transferring ownership to a new buyer is the next best thing. Refurbishing or remanufacturing the product is a good third choice. (Remanufacturing is dismantling a product to reuse its components.) Reusing the features that make up the product is the fourth best choice.

2) Material Substitution: One of the key strategies for reducing industrial GHG emissions can be found in substituting lower embodied carbon materials for higher incorporated carbon materials in products. The primary source of GHG emissions is the product category of building materials, mainly concrete and steel [8]. These emissions account for over 10% of all world emissions in total. Very few alternative materials are available in amounts adequate to appreciably reduce consumption due to their vast scale 4 Gt/year of cement production and 1.8 Gt/year of steel manufacturing [9]. Two frequently discussed prospects for substitution at scale in the construction industry are the use of timber-based products and the partial replacement of cement with supplemental cementitious materials [10].

3) Longevity, intensity, and material efficiency: For substitution, it is most frequently considered when steel may be substituted with aluminium, carbon fibre, or other solid and lightweight materials, boosting the vehicles’ fuel efficiency. Compared to the heavier materials they replace, these materials frequently have higher embodied emissions per vehicle. Fortunately, the energy and greenhouse gas emissions saved by a light car during its lifetime typically outweigh the additional energy and emissions incurred in producing its unique materials. Understanding the trade-offs and demonstrating where material replacement makes sense can be made via life cycle assessments (covering manufacturing, usage, disposal, and recycling ability. By increasing the efficiency of the materials, emissions can be reduced, and materials can be used for longer periods of time

B. Supply side technologies

1) Hydrogen: Using hydrogen as a fuel is one of the essential techniques practiced in industrial processes such as producing fertilizers, metal treatment, refining petroleum, and as catalysts in producing ammonia. Hydrogen is produced primarily through steam reforming, coal gasification, and electrolysis. It is formed as a byproduct of different industrial processes such as the Direct reduction of steel & iron making and the production of NaOH (Sodium Hydroxide) and Chlorine (Cl) in chlorine.

Around 30Mt of hydrogen is produced yearly as a by-product in industrial processes. Most H2 produced is used across several industries, such as ammonia, methanol, refineries of oil, and other sectors 43%, 34%, 17%, and 6%, respectively. Around 0.01% of H2 is used in fuel-cell electric vehicles.

2) Electrification: The industrial process requires a significant amount of fuel to produce heat. It is primarily used for processing heat, fueling the boiler, and other end-use uses. Electrification plays a crucial role in the decarbonization of industrial sectors. Different materials respond differently to electromagnetic energy. Compared to conventional, fuelbased process heating operations, there may occasionally be a transformation pathway that yields the necessary output product with less overall heat input. However, Technologies based on electricity have higher efficiency and lower thermal requirements than traditional methods of operation. Electric arc furnaces, resistive heating, and laser sintering are examples of specific uses where thermal heat can be replaced by electricity [5].

3) Energy efficiency: Improvements in energy efficiency can reduce water use, greenhouse gas (GHG) emissions, and other pollutants. It can be achieved through enhancement in the design of materials, efficient heat recovery and steam systems, and implementation of energy-efficient design for industrial sectors. Efficiency improvements are categorized based on their performance and effect on energy, mass, and information. It can also considerably improve efficiency by optimizing production processes and implementing the best available technologies. However, implementing efficiency measures leads to several benefits. It includes lowering the energy cost, creating a reliable supply of power, and reduction in greenhouse emissions IEA.

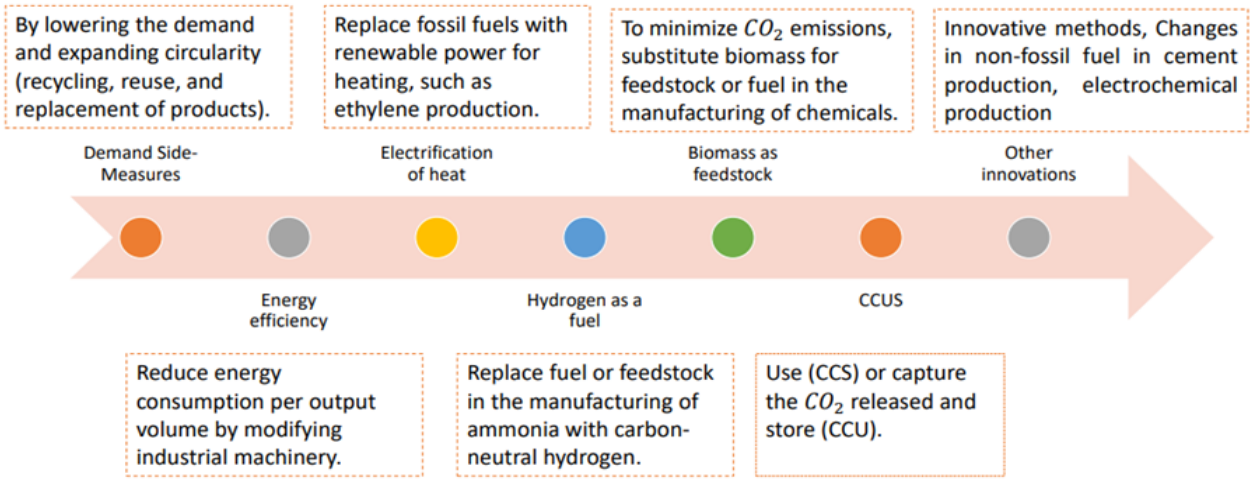


Fig. 1. Decarbonization option

3. Position Statement

Energy-intensive industries can achieve net-zero emissions through a strategic combination of emerging technologies (like green hydrogen, CCS, and electrification), enabling policy frameworks, and a socio-economically just transition especially in emerging economies like India where economic spurt and sustainable practices must be balanced. methods of operation. Electric arc furnaces, resistive

Key Arguments & Supporting Evidence

A. Cement Industry

Cement is one of the most used materials worldwide for several purposes. Cement production is one of the industrial sectors' that contributes significantly to greenhouse gases. Energy use and calcination reactions are the two primary processes that emits GHG during cement manufacture. When thermal fuels, most frequently coal, are used to heat a precalciner, and rotary kiln results in emissions of greenhouse gasses. The precalciner, where limestone CaCO3 is broken down into lime (CaO) and carbon dioxide, is the other primary source of direct GHG emissions. Cement has several applications across the world.

Primary applications include binder in concrete, which is used as a primary material for construction, such as roads, housing, schools, ports, and dams. Several decorative applications include patios, floors, driveways, pool decks, tables, and sculptures. In cement production, major sources of GHG emissions are the production of clinkers. In present scenarios, Several techniques are used to reduce greenhouse gasses. They are substitutions of alternative clinkers, electrification, CCUS, and fuel switching.

B. Iron & steel

Iron and steel are used widely for several applications, such as railways, roads, buildings, and other infrastructures. It is produced through chemical reactions inside the blast furnace. The raw materials in blast furnaces are heated at a high temperature (2200°C) which leads to the formation of molten Iron and liquid slag, as shown in fig . The molten Iron, also called pig iron, consists of a high concentration of carbon. It consists of various impurities, i.e., sulphur, carbon, silicon, manganese, and phosphorus. These impurities are removed through oxidation, and the temperature inside the blast furnace is controlled by the amount of scrap steel and iron ore. In the next step, steel is separated from the blast furnace, and the slag is recycled. The production of cement contributes significantly to greenhouse emissions. Industries are opting for electric arc furnaces to mitigate these emissions despite Basic oxygen furnaces for producing Iron & steel.

C. Chemical

The primary source of GHG emissions in the chemicals sector is the combustion of fossil fuels; hence the development of methods to lower these emissions should be prioritized. Effective strategies could be improved for usage in the industry [4]. For instance, to break down naphtha for further processing, steam crackers need to achieve a temperature of 850 °C. GHG emissions might be cut by up to 90% if this energy could be generated using electricity with no emissions. Six major chemical producers (BASF, Borealis, BP, LyondellBasell, Sabic, and Total) have collaborated to research the development of the first electrical steam crackers or naphtha crackers. New catalysts can lower the energy needed to initiate various chemical reactions. For instance, modern catalyst systems enable the dry reforming of methane CH4 into dimethyl ether (CH3OCH3), which can then be converted into a variety of olefins, including ethylene (C2H4), the most abundant organic chemical in the world. A more comprehensive choice of energy-efficient solutions, including ones with negative lifetime costs, are available to manufacture chemicals.

D. Ammonia

Ammonia is one of the products used in the chemical industry to produce fertilizers such as ammonium carbonate and Urea [10]. Ammonia is used as a fuel and energy carrier for several industrial purposes. These multiple applications of Ammonia have led to an increase in demand, which further leads to increased CO2 emissions. Among several industrial processes, ammonia production contributes to air pollutants such as CO2, SO2, and NOx emissions. Reducing emissions and saving energy can be achieved by improving energy efficiency, transition path, and emission characteristics. Nowadays, natural gas is preferred in the gas formation process. In addition to achieving the deep decarbonization target, using a cleaner electrolysis-based ammonia process and adopting CCUS techniques can reduce this emission by 98% in these industries cite.

E. Paper & Pulp

Paper is one of the essential products with several applications, such as printing, painting, graphics, signage, design, packaging, decorating, writing, and cleaning. It is produced through a physical and chemical process that involves soaking cellulose fibers from wood, rags, grass, or other vegetable sources. Water is drained through a fine mesh, so the fibers are evenly dispersed, press the material and let it dry. The pulp is the primary component in producing paper, which is created by dissolving the fibrous section of plants, primarily trees or recycled paper. The most typical source of fiber for papermaking and the foundation for many paper and wood goods is wood fiber or pulp derived from trees. Paper and pulp industries contribute significantly to greenhouse gasses. Different techniques, such as waste paper recovery and paper and cardboard recycling, can reduce these emissions.

5. Policy Recommendations

1) Carbon Pricing: Carbon pricing, which requires emitters to pay a fee per tonne of CO2 (or, better yet, per tonne of GHGs, measured in CO2-equivalent) they emit, is one of the most well-known emissions-reduction strategies. Carbon pricing enables regulators to limit GHG emissions from the industry sector cost-effectively without the need to develop expertise in manufacturing processes, as might be necessary to set emissions standards for specific types of equipment or per unit of a commodity. Emitters are free to choose the least expensive way to reduce emissions or to pay the carbon price in cases where emissions reduction is expensive [5].

2) Emission Standards: The government makes these standards to reduce air pollution from factories and other industrial facilities. Standards are binding requirements that specify maximum allowable levels of contaminants from a specific source. Energy efficiency regulations for appliances, equipment, and vehicles are among the most potential governmental initiatives for reducing energy use in the present scenario. Motors account for two-thirds of industrial electricity consumption; electric motor standards have significantly lowered electricity consumption during operation.

3) Low-carbon materials and product labelling: The uses of low-carbon materials and goods play a crucial role in decarbonizing industrial sectors. There is a need to encourage the markets for low-carbon goods. Similar to current labelling programs for energy-efficient appliances, lighting, windows, and other products, labels for some finished products may be directed at consumers. However, they would disclose manufacturing-related GHG emissions rather than the product's energy efficiency.

4) Recycle requirements or incentives: Recycling of materials in several industries can decrease emissions in these sectors. For some commodities, like steel and aluminum, the inherent value of the waste materials may be high enough to make recycling worthwhile financially and logistically. Even these materials, meanwhile, are frequently not recycled. For instance, only 33% of steel and 19% of aluminum in municipal solid waste (MSW) are recycled .

5) Building Codes: Buildings are essential to human wellbeing, and their construction accounts for a sizable portion of economic activity. (For instance, 8% of the US GDP). The production of materials, primarily structural materials like steel and concrete, accounts for over 20% of global energy and process-related GHG emissions. Construction, therefore, has a significant environmental impact.

Conclusion

Decarbonizing industrial sectors presents several challenges:

- Many industrial processes require high-temperature heat (>500°C), which is difficult to generate using renewables.
- Processes are deeply integrated, making modifications complex.
- Industries have long lifespans and high capital costs, limiting flexibility.
- Reducing feedstock emissions often requires switching to cleaner alternatives like hydrogen or biomass.

This paper reviews demand- and supply-side technologies that support industrial decarbonization. Key sectors cement, steel, and chemicals account for over 80% of projected CO_2 reductions between 2015 and 2050. Tackling overcapacity and deploying energy-saving, emission-reducing technologies in these sectors is critical. In others (e.g., textiles, mining, agriculture), electrification—expected to reach 80% by 2050 is the main strategy. Hydrogen and CCUS are also expected to play vital roles in achieving industrial carbon neutrality.

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10. Rewiring Sustainability in Commercial Transport: An LCA-Based Comparison of TATA ACE ICE and EV Model

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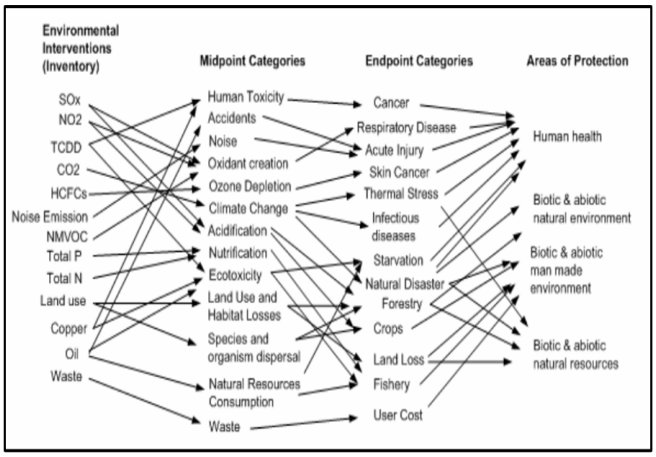
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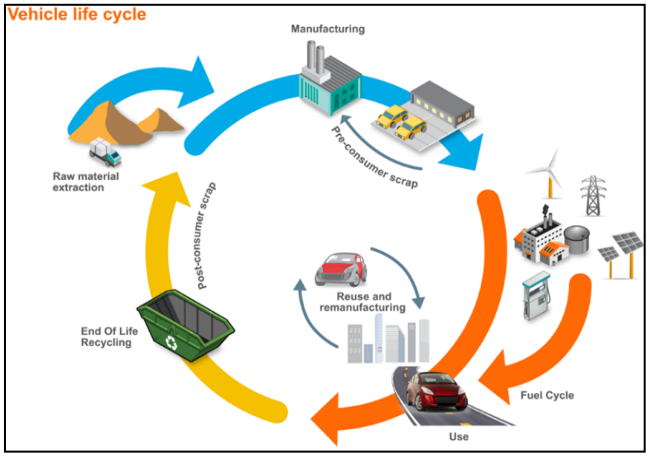
Executive Summary

This position paper presents key insights from a Life Cycle Assessment (LCA) comparing the environmental performance of Tata Motors' most popular commercial mini truck Tata Ace in its Internal Combustion Engine (ICE) and Electric Vehicle (EV) variants. Utilizing SimaPro software and the ReCiPe Midpoint 2016 methodology, the study evaluates cradle-to-grave environmental impacts, including Global Warming Potential (GWP), resource depletion, toxicity, and fossil fuel consumption.

The Tata Ace EV demonstrates a 41% lower GWP than its ICE counterpart, driven by zero tailpipe emissions during the use phase. However, the EV's advantages are partially offset by increased toxicity and resource depletion, especially from battery production and raw material extraction of lithium and copper. When the electricity mix is shifted to 100% renewables, the EV's environmental performance significantly improves across categories This paper argues that while EVs are aligned with national decarbonisation goals, strategic interventions are needed to mitigate upstream and end-of-life environmental burdens. Recommendations include improving battery recycling, adopting circular economy strategies, integrating cleaner energy in manufacturing, and regionalising EV supply chains.

The position is clear: the Tata Ace EV represents a significant leap forward in sustainable mobility for India's commercial vehicle sector—but only if the environmental trade-offs are proactively managed. Policymakers and manufacturers must act jointly to accelerate India's low-carbon transition while ensuring resource efficiency and ecological safety. The insights from this LCA offer a roadmap to shape future-ready commercial vehicle development rooted in sustainability and resilience.





Context and Problem Statement

India's commercial vehicle sector is undergoing a significant transformation, driven by the twin forces of policy reform and environmental urgency. Government schemes like the Faster Adoption and Manufacturing of Electric Vehicles (FAME II), the National Electric Mobility Mission Plan (NEMMP), and India's commitment to achieving Net-Zero emissions by 2070 are pushing automakers and fleet operators toward electrification. At the heart of this shift lies a fundamental question: Are electric vehicles (EVs) truly more sustainable than conventional Internal Combustion Engine (ICE) vehicles when viewed across their entire lifecycle?

The Tata Ace, one of the country's most sold and widely used commercial mini trucks, provides a representative case to explore this question. It serves thousands of micro-entrepreneurs, small traders, and last-mile delivery operators across India. With diesel still dominating the light commercial vehicle (LCV) market, the introduction of the Tata Ace EV is seen as a step toward greener logistics. But behind the promise of zero tailpipe emissions lies a more complex reality.

Most discussions around EVs are narrowly focused on the use phase, highlighting reduced local air pollution and zero operational emissions. However, these benefits can be misleading if not contextualized within the entire life cycle of the vehicle—from raw material sourcing, battery manufacturing, and grid electricity mix to end-of-life battery disposal and recycling. The environmental impact of extracting lithium, cobalt, and copper; the carbon footprint of battery production; and the challenges of battery end-of-life treatment pose serious concerns that must be evaluated.

Moreover, India's electricity grid remains predominantly is coal-based. Charging an EV on this grid could offset many of the environmental benefits unless renewable energy integration is prioritized. In such a scenario, a cradle-to-grave Life Cycle Assessment (LCA) becomes essential to understand the full spectrum of environmental trade-offs.

This paper responds to that need. By conducting a comparative LCA of the Tata Ace ICE and EV variants, it seeks to quantify emissions, resource consumption, and toxicity impacts across each life cycle stage. The aim is not just to validate the benefits of EVs but to uncover the hidden costs and systemic inefficiencies that may otherwise be overlooked.

In doing so, this paper contributes to the evolving discourse on sustainable transportation in India. It provides a nuanced view that can inform policy, shape manufacturing strategies, and guide investment in cleaner, more circular technologies for the commercial vehicle segment

Literature Review

In recent years, the comparative sustainability of Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles has become a critical subject of research, particularly through the lens of Life Cycle Assessment (LCA). Unlike tailpipe emission comparisons, LCAs allow a more complete evaluation by including upstream and downstream impacts from raw material extraction and manufacturing to usage and end-of-life processing.

Hawkins et al. (2013) emphasized that while EVs significantly reduce operational emissions, their overall environmental advantage is tempered by the carbon-intensive processes involved in battery manufacturing and raw material sourcing. Similarly, Ellingsen et al. (2016) highlighted that environmental outcomes for EVs are highly sensitive to electricity grid mix and battery disposal strategies, making localized studies essential.

In the Indian context, Jain and Sharma (2018) pointed out that the benefits of EVs are significantly diluted by India's coal-heavy electricity grid. They argued that unless cleaner energy sources are adopted, the net GHG reduction from EVs remains marginal.

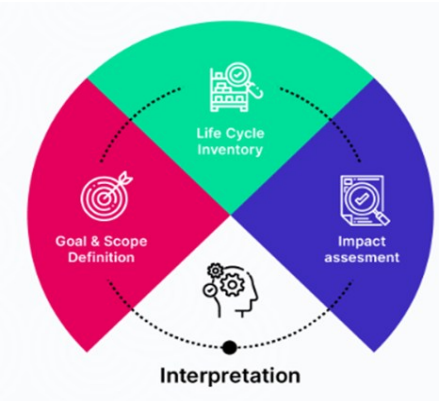
Raghavan et al. (2017) advanced this understanding through scenario-based modeling, demonstrating that with higher renewable energy penetration, EVs show clear environmental advantages over ICE vehicles.

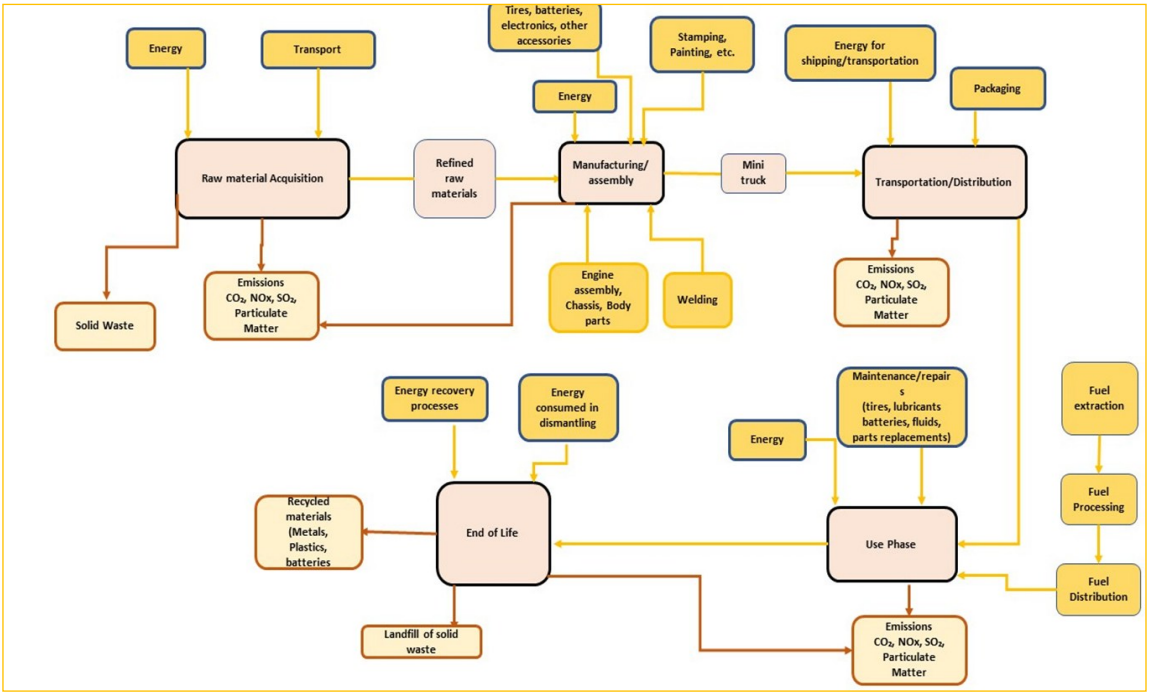
Kumar et al. (2019) focused specifically on commercial EVs and noted that while operational emissions are notably lower, the environmental burden shifts to upstream activities, particularly mining and manufacturing.

Their work underlined the need for policy frameworks that go beyond end-use emissions and encourage sustainable sourcing, manufacturing, and recycling practices. More recently, Singh et al. (2020) and Sharma, Gupta, and Bansal (2021) stressed the role of circular economy practices in improving the lifecycle performance of EVs. These include design for disassembly, battery second-life use, and advanced material recovery techniques all of which can substantially mitigate the resource depletion and toxicity impacts of EVs.

Despite these advancements, literature remains limited when it comes to LCA studies on light commercial mini trucks, especially in the Indian context. Given the Tata Ace's widespread usage and relevance to last-mile connectivity, an LCA focused on its ICE and EV variants fills a crucial gap. It brings specificity to a category often generalized under passenger or heavy-duty vehicle research and adds practical value for policymakers, industry leaders, and sustainability professionals. This paper builds upon the global LCA discourse and adapts it to the Indian commercial vehicle landscape delivering both contextual relevance and actionable insights.

This study aims to evaluate and compare the environmental performance of the Tata Ace ICE and EV variants using a cradle-to-grave Life Cycle Assessment (LCA) approach. The goal is to move beyond superficial emissions comparisons and instead provide a comprehensive, evidence-based assessment of environmental trade-offs associated with transitioning from diesel-powered to electric mini trucks in India's light commercial vehicle (LCV) segment.





The functional unit for this assessment is one Tata Ace vehicle (either ICE or EV) operating over a lifespan of 150,000 kilometers. The system boundary includes all major life cycle stages: raw material extraction, manufacturing, transportation, use phase, and end-of-life treatment, including disposal and recycling. This ensures a holistic perspective, capturing direct and indirect environmental burdens.

Environmental impact categories assessed include:

- Global Warming Potential (GWP)
- Fine Particulate Matter (PM2.5) Formation
- Fossil and Mineral Resource Depletion
- Water Consumption
- Human and Ecotoxicity

The analysis is performed using SimaPro 9.0 software, based on the ReCiPe Midpoint 2016 methodology. Primary data is collected from Tata Motors' Pantnagar plant, with supplementary data sourced from the Ecoinvent database and peer-reviewed academic literature.

To deepen the analysis, the study integrates four analytical layers:

- **Comparative Analysis –** Directly compares environmental impacts across both vehicle variants for each impact category.
- **Hotspot Analysis –** Identifies which life cycle stages contribute most to overall impact (e.g., use phase for ICE; battery production for EV).
- **Trade-Off Analysis –** Evaluates areas where environmental gains (e.g., reduced GHG emissions in EVs) come at the cost of increased burdens elsewhere (e.g., higher resource depletion and toxicity).
- **Scenario Analysis –** Models the EV under three electricity grid scenarios:
  - Business-as-usual (70% fossil-based grid)
  - 50% Renewable Energy
  - 100% Renewable Energy

These scenarios help assess the sensitivity of EV performance to India's evolving energy mix and inform future policy direction.

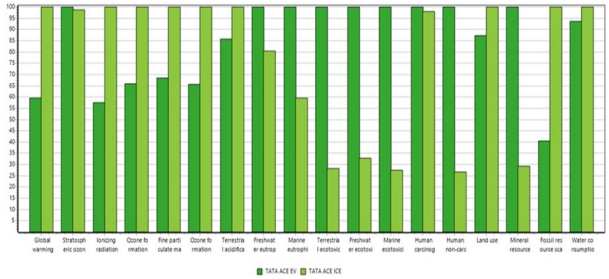
The combination of real-world data, standardized LCA tools, and scenario modeling ensures that the findings are not just academically robust but also practically relevant. By focusing on the Tata Ace—an icon of India's small-scale logistics economy—this study provides insights that are directly applicable to the country's mobility and sustainability transition.

Key Findings and Arguments

The Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants reveals a complex sustainability landscape that cannot be judged solely by tailpipe emissions. This section presents the four core analytical dimensions—comparative analysis, hotspot analysis, trade-off analysis, and scenario analysis—to deliver a complete picture of environmental performance.

1. Comparative Analysis

The Tata Ace EV outperforms the ICE variant in terms of Global Warming Potential (GWP), emitting approximately 28,712 kg CO_2 eq over its lifecycle, compared to the ICE's 48,166 kg CO_2 eq—showing a 41% reduction. The EV's advantage lies in its zero tailpipe emissions during the use phase.



However, when toxicity-related impacts are considered, the picture changes. The EV exhibits significantly higher terrestrial and freshwater ecotoxicity—almost 3.5 times more than the ICE model—mainly due to battery production and material processing. Additionally, the EV scores poorly in mineral resource scarcity, driven by the demand for lithium, cobalt, and copper used in battery and motor components.

2. Hotspot Analysis

Hotspot analysis pinpoints the life cycle stages that contribute most to each environmental category:

ICE Variant: The use phase is the largest contributor to GWP, particulate matter, and acidification impacts, primarily due to diesel combustion. Manufacturing is also a EV Variant: The environmental burden shifts upstream. Material acquisition (especially battery materials) and manufacturing are the dominant contributors to GWP, toxicity, and resource depletion. The EV's use phase is significantly cleaner, but indirect emissions from electricity production must be accounted for.

End-of-Life Phase: Although relatively minor in overall impact, EVs pose challenges due to battery recycling, which introduces additional toxicity and energy demand major contributor due to steel and aluminum use.

3. Trade-Off Analysis

The shift from ICE to EV is not an environmental panacea; it involves trade-offs:

- GHG vs. Resource Depletion: While the EV cuts GHG emissions, it increases demand for non-renewable resources. For instance, the mineral resource scarcity of the EV is 434.55 kg Cu eq compared to the ICE's 126.62 kg Cu eq.
- Air Quality vs. Toxicity: The EV variant significantly reduces particulate emissions (82.43 kg PM2.5 eq vs. 120.22 kg PM2.5 eq for ICE), but introduces higher risks in terms of human and ecological toxicity, which are often overlooked in policy frameworks.
- Operational Gains vs. Manufacturing Burden: The use-phase benefits of EVs are undermined by emissions and resource use in battery manufacturing, transport (especially international battery imports), and raw material extraction.
- These trade-offs reinforce the need for innovations in battery chemistry, lightweight materials, and closed-loop recycling systems.

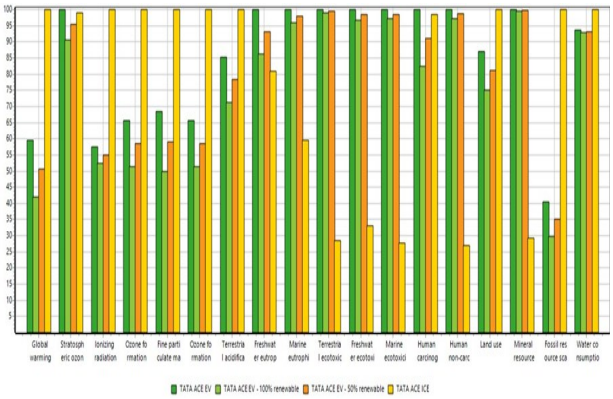
4. Scenario Analysis

- To assess how India's electricity grid influences EV sustainability, the study modeled three scenarios:
- Business-as-usual (70% fossil-based grid): EV emits 28,712 kg CO_2 eq—better than ICE but not dramatically.
- 50% Renewable Grid: EV emissions reduce to ~24,450 kg CO_2 eq, with noticeable improvements in GWP and air quality indicators.
- 100% Renewable Grid: EV emissions drop to ~20,235 kg CO_2 eq—a 58% reduction from ICE baseline and nearly 30% better than the business-as-usual EV.

While toxicity impacts remain, they also marginally improve due to cleaner electricity in manufacturing and charging.

Synthesis

Taken together, the data suggests that while the Tata



Ace EV aligns with India's climate goals, its sustainability benefits are conditional—not guaranteed. The vehicle's overall environmental profile is influenced more by how it is made, powered, and disposed of, rather than simply by the fact that it's electric.

This reinforces a crucial argument: for EVs to become truly sustainable, interventions are needed across the entire value chain—from sourcing of minerals to design for disassembly, and from grid decarbonization to robust battery take-back systems.

The Tata Ace EV can serve as a catalyst for transforming India's small commercial vehicle market—but only if the systemic trade-offs are acknowledged and addressed through coordinated industrial, technological, and policy measures.

Policy and Practice Implications

The comparative Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants reveals that while EVs offer significant environmental benefits in terms of greenhouse gas emissions, these advantages are tempered by challenges related to resource depletion, toxicity, and energy sourcing. To truly realize the promise of sustainable electric mobility in India's commercial vehicle sector, multi-stakeholder actions are required. The following are the key policy and practice implications derived from this study:

1. Innovation in Battery Design and Circularity

The high environmental burden of battery manufacturing highlights the urgent need for innovation in battery design. Policymakers must incentivize research in next-generation battery chemistries—such as solid-state and sodium-ion technologies—that are less resource-intensive. Additionally, automakers should adopt circular economy principles such as modular battery packs and second-life applications to improve recyclability and reduce raw material dependence.

2. Renewable Energy Integration in Manufacturing and Charging

The scenario analysis clearly shows that the environmental performance of EVs improves substantially with cleaner energy. It is therefore imperative that both government and industry push for higher renewable energy adoption at manufacturing sites and EV charging stations. Tata Motors and other OEMs can set an example by shifting their plant operations to solar and wind-based energy sources.

3. Localized Supply Chains and Sustainable Procurement

Transport emissions and material sourcing impacts can be reduced by localizing supply chains. Tata Motors should consider sourcing battery components and metals domestically where possible, reducing the need for carbon-intensive imports. Further, suppliers should be evaluated on sustainability parameters including ethical mining practices and environmental compliance.

4. Lifecycle-Based Policy Incentives

Current EV incentives are largely based on upfront purchase price and use-phase emissions. A shift toward lifecycle-based incentive structures—where vehicles with lower cradle-to-grave impacts receive higher support—will encourage more responsible product design and sourcing. Policy frameworks such as FAME III should integrate lifecycle metrics for subsidy disbursement.

5. Battery Recycling Ecosystem Development

India currently lacks a formal, scalable battery recycling system. The government must accelerate the implementation of Extended Producer Responsibility (EPR) rules, and support the development of advanced recycling infrastructure. Collaborations between OEMs, startups, and public agencies can enable closed-loop systems that recover valuable materials and reduce environmental harm.

By addressing these critical areas, India can move beyond incremental improvements and toward transformative change in the commercial EV segment. The Tata Ace EV, as a high-volume, widely recognized vehicle, has the potential to serve as a scalable model for sustainable last-mile logistics if supported by bold and holistic action from both policymakers and industry.

Conclusion

The comparative Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants presents a nuanced, evidence-backed understanding of what sustainable mobility truly entails in the Indian context. While the EV model clearly reduces operational emissions and aligns with India's climate objectives, the environmental costs associated with upstream battery production, material sourcing, and end-of-life recycling cannot be overlooked.

This study's multi-dimensional framework spanning comparative metrics, hotspot analysis, trade-offs, and future energy grid scenarios demonstrates that environmental performance is not just about what a vehicle emits on the road, but also about how it is manufactured, powered, and disposed of. For instance, the EV's Global Warming Potential drops significantly under a 100% renewable energy scenario, yet its toxicity and resource depletion impacts remain areas of concern unless addressed through system-level innovations.

The key takeaway is this: EVs like the Tata Ace represent a critical opportunity to decarbonize India's small commercial vehicle fleet, but this transition must be managed thoughtfully. Sustainability cannot be treated as a checkbox. It requires collaboration across policy, technology, supply chain, and public awareness.

To unlock the full potential of the Tata Ace EV, India must invest in cleaner manufacturing, renewable energy infrastructure, localised supply chains, and a robust battery recycling ecosystem. This paper makes the case for a lifecycle-thinking approach one that ensures the country's low-carbon ambitions are not achieved at the cost of new ecological burdens.

With strategic interventions, the Tata Ace EV can become not just a zero-emission vehicle but a symbol of holistic, responsible, and future-ready mobility.

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Harnessing the Sun Responsibly: The Impact of Solar Technology on Agriculture and Public Health

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Executive Summary

This paper explores the multifaceted impact of solar technology on three critical pillars of rural development in India: agriculture, public health, and environment. With solar energy now a core component of climate change mitigation efforts, particularly through initiatives like the PM-KUSUM scheme, its application in rural areas has grown exponentially. The key objective of this paper is to assess how solar electrification—mainly through solar-powered irrigation, mini-grids, and rooftop systems—affects agricultural productivity, health infrastructure, environment and livelihoods.

Main findings indicate that solar technology reduces operational costs and air pollution, thereby enhancing both agricultural output and respiratory health. However, the benefits are often tempered by unintended consequences such as groundwater depletion, soil degradation, and uneven access due to policy and infrastructural gaps. Economically, while solar adoption boosts farm income and rural enterprise, its positive effects are not evenly distributed across socio-economic groups. The implications of these findings call for a holistic and integrated policy approach. Solar technology, while beneficial, must be deployed in a manner that anticipates ecological trade-offs, enhances policy coherence, and ensures equitable access. This paper argues for the adoption of cross-sectoral planning frameworks such as the Water-Energy-Food Nexus and highlights the need for regulatory reforms that link solar energy deployment with water and land-use governance.

Position Statement: Solar technology holds transformative potential for sustainable development in India, but its success depends on addressing ecological, social, and governance challenges through integrated and inclusive policy mechanisms.

Context and Problem Statement

India's transition drive towards clean energy has made solar technology central to its development agenda, particularly in rural areas. The country's National Solar Mission and schemes like PM-KUSUM aim to decentralize energy access, reduce greenhouse gas emissions, and empower rural livelihoods. However, the rapid and often unregulated expansion of solar electrification raises critical questions about its long-term sustainability and socio-environmental implications.

In agriculture, solar-powered irrigation systems (SPIS) have significantly reduced dependence on diesel and improved access to reliable water sources. This has led to improved productivity and crop diversification. However, studies have shown that the zero marginal cost of operating solar pumps encourages excessive groundwater extraction, particularly in water-stressed states like Rajasthan and Gujarat. This threatens aquifer sustainability, contributes to land degradation, and undermines climate adaptation goals.

Similarly, the health sector benefits from improved lighting, refrigeration, and water pumping enabled by solar mini-grids and rooftop systems. These advances support vaccine preservation, night-time deliveries, and disease diagnostics. Nevertheless, rural clinics often lack

capacity to maintain these systems, limiting their effectiveness. Furthermore, improper disposal of solar panels and batteries introduces new environmental health risks due to the presence of toxic materials. Economically, solar technology enhances productivity, reduces input costs, and creates employment opportunities in installation and maintenance. Yet, access to subsidies and solar infrastructure remains skewed in favor of large and medium farmers. Marginalized groups, including women and smallholders, face barriers such as high upfront costs, lack of land ownership, and limited technical training. This exacerbates existing socio-economic disparities and undermines the goal of inclusive development.

The main problem isn't just how solar systems are being used, but the fact that policies around energy, water, and agriculture often work in isolation instead of supporting each other. Energy policies often conflict with water conservation goals, while health and agriculture policies fail to integrate energy considerations. This lack of policy coherence limits the ability of solar technology to deliver sustainable, equitable outcomes across sectors. This paper addresses these challenges by evaluating the environmental, economic, and public health impacts of solar technology. It seeks to fill the gap in existing research by proposing integrated policy solutions that bridge sectoral divides. The analysis underscores the urgent need for governance frameworks that align solar deployment with sustainable water use, soil conservation, and inclusive access.

Literature Review

Researchers have increasingly examined how solar power affects farming, health services, and livelihoods in rural India. A key area of consensus is the potential for solar-powered irrigation to reduce reliance on diesel and lower input costs for farmers. Studies show significant improvements in farm economics through solar pump adoption, yet also caution against groundwater overuse in the absence of regulatory controls (Kumar, 2020) (Shah, 2018) (Yale, 2023) . Environmental studies show both benefits and downsides: solar energy helps cut emissions and pollution, but large solar parks can disturb local ecosystems and change land use patterns. (Dupraz et al., 2011) (Singh, 2019). Solar infrastructure can also impact local climates, including the emergence of the Photovoltaic Heat Island (PVHI) effect in arid regions (Hernandez et al, 2014), a phenomenon supported by on-ground reports from Modhera.

.In public health, solar electrification has enabled improved vaccine storage, nighttime medical care, and reduced dependence on biomass-based fuels. The transition to clean energy has been linked to decreased respiratory illnesses and improved maternal health outcomes (WHO, 2016) (Dasgupta, 2019). However, concerns about toxic waste from end-of-life solar panels and batteries are increasingly prominent (Li, 2022), a topic largely absent from rural health and environmental regulations.

Government reports often celebrate schemes like PM-KUSUM, but they also show that poor coordination between solar, water, and agriculture policies reduces their overall impact. (GoI, 2021) (MNRE, 2023) The Ministry of Environment, Forest and Climate Change (MoEFCC) has emphasized the need for low-carbon transitions aligned with conservation goals, but implementation remains fragmented (MoEFCC, 2022). NITI Aayog has also pointed to the role of decentralized solar power in advancing Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), and SDG 7 (Affordable and Clean Energy) (Aayog, 2020) (NITI Aayog). Globally, UNDP underscores the cross-cutting nature of solar technology in achieving the SDGs, advocating for inclusive energy policies that address environmental sustainability, equity, and health (UNDP, 2021). The Water-Energy-Food (WEF) Nexus approach has been highlighted as a guiding framework to harmonize these objectives (Bazilian, 2020)(Larsen, 2020)

Social equity issues are well-documented. Existing subsidy structures tend to favor wealthier and male-headed households, marginalizing women and smallholders (Shankar, 2019). Gender disparities persist in access, training, and participation in solar energy governance (Baruah, 2015) (GIZ, 2021).

In summary, while the literature validates solar energy's benefits, it also reveals critical gaps in environmental oversight, policy coherence, and social inclusivity. This paper builds upon these findings to evaluate the on-ground realities of solar deployment and inform more integrated and just development strategies.

Research Focus and Methodology

Research Design

This study employs a mixed-methods research design, combining quantitative data from surveys and secondary statistics with qualitative insights from field observations and key informant interviews. The approach was chosen to capture both the measurable impacts of solar energy adoption and the contextual, lived experiences of communities affected by its deployment.

The methodology aligns with the study's multi-sectoral focus on agriculture, public health, and environment. It emphasizes a comparative case study approach to understand regional diversity, social dynamics, and ecological outcomes.

Study Area

Four villages across four different Indian states were selected to represent agro-ecological, cultural, and policy diversity

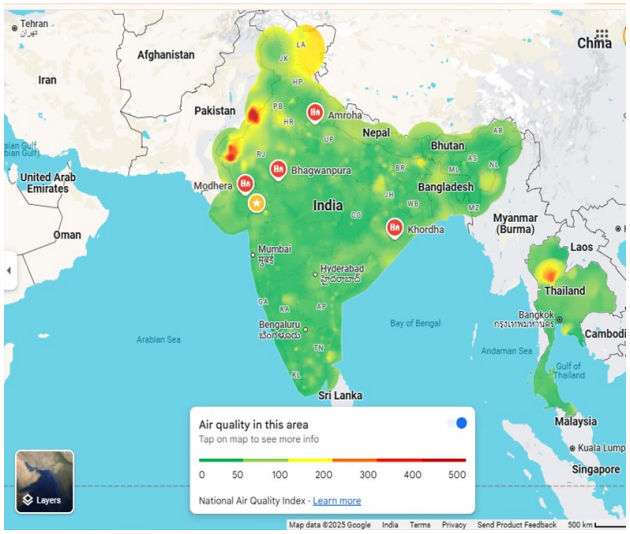
- Modhera (Gujarat): A state-supported solar village with a microgrid and extensive rooftop solar adoption.
- Baripatha (Odisha): A tribal village electrified via solar mini-grid, known for SHG-based micro-enterprises.
- Amroha (Uttar Pradesh): A semi-urban community with limited solar pump adoption and persistent grid instability.
- Bhagwanpura (Madhya Pradesh): An agrarian village with PM-KUSUM implementation and groundwater stress.

These sites were selected based on purposive sampling to represent diverse solar applications (irrigation, health, mini-grid), different governance frameworks, and varying ecological conditions.

Data Collection Methods

- Primary Data

- Household Surveys: Structured surveys were conducted with 150 respondents (approx. 35–40 per village), covering farmers, health workers, SHG members, and solar entrepreneurs.
- Key Informant Interviews: Semi-structured interviews with 20 stakeholders, including:
  - ◊ Agricultural extension officers
  - ◊ Renewable energy agency officials
  - ◊ Panchayat leaders
  - ◊ Health facility staff



- Field Observation: System performance, usage behaviours, maintenance conditions, and local impacts were documented during site visits.

Secondary Data

- Government documents and reports (MNRE, MoEFCC, NITI Aayog)
- Journal articles, field studies, and case evaluations
- Open-access spatial data (e.g., solar irradiance maps, groundwater reports, land use data)

Data Analysis Techniques

- Quantitative Data

- Descriptive statistics (mean, frequency, standard deviation) were used to analyze survey responses related to irrigation patterns, crop yields, energy savings, and health service usage.
- Cross-tabulation and correlation analysis were employed to examine relationships between solar usage and outcomes across different socio-economic groups.

- Qualitative Data

- Thematic analysis was used to code and analyse interviews and observations, focusing on categories such as environmental impact, equity, access, and governance.
- Narrative synthesis helped interpret conflicting or region-specific outcomes.

Limitations of the Methodology

- The study was constrained by limited access to long-term groundwater and health data at the village level.
- Seasonal variability and recall bias may have affected responses, especially concerning crop yields and water use.
- While efforts were made to ensure representation

Table:1

Village	Gender	Sum of Doctors	Sum of Farm Superintendents	Sum of Farmers	State
Amroha	Male	2	5	10	Uttar Pradesh
Baripatha	Male	2	5	10	Odisha
Bhagwanpura	Male	2	5	10	Madhya Pradesh
Modhera	Male	2	5	10	Gujarat

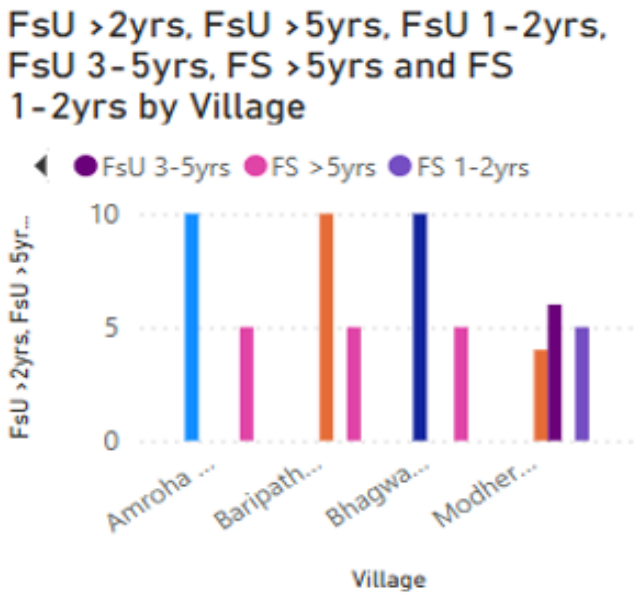
Total: 40 Farmers, 20 FS, 8 Doctors = **68 respondents**

Table:2

FsU >2yrs	FsU >5yrs	FsU 1-2yrs	FsU 3-5yrs	FS >5yrs	FS 1-2yrs	Village	State
10	0	0	0	5	0	Amroha (UP)	
0	0	10	0	5	0	Baripatha (Orissa)	
0	10	0	0	5	0	Bhagwanpura (MP)	
0	0	4	6	0	5	Modhera (Gujarat)	

FsU: Farmer's Usage , FS : Farmer Superintendent Usage

Figure:2



across gender and caste, some marginalized voices (e.g., landless migrants) may remain underrepresented.

Key Findings and Arguments

Overview of Sample Distribution

This research includes 68 participants drawn from four solar-enabled villages across India:

Impact on Agriculture

- Productivity and Irrigation

All 40 farmers across the four villages reported increased productivity with solar integration. However, increased water usage was also reported by all farmers in every village, with soil and crop changes noted by farmers and FS in Bhagwanpura (MP) alone.

Table:3

Village	Productivity Increased (All)	Water Usage Increased (All)	Soil/Crop Change Observed
Amroha (UP)	Yes	Yes	No
Bhagwanpura (MP)	Yes	Yes	FS: 2 Yes, 3 No
Modhera (Gujarat)	Yes	Yes	No
Baripatha (Orissa)	Yes	Yes	No

Discussion: While increased productivity matches studies like Closas & Rap (2017), unregulated water extraction poses long-term risks. Bhagwanpura's observed soil/crop

change is early evidence of shifting agro-ecological patterns due to excess irrigation.

Impact on Agriculture

- Financial Aspects: Cost and Support

- Farmer Initial Cost Concern: ~57.85% showed concern over upfront costs.
- Farmer Financial Support Access: Only 20–30% of farmers received financial support (lowest in Modhera, highest in Baripatha).
- Subsidy Access: Less than 30% of farmers received subsidies in any village.

Table: 4

Village	Farmer Initial Cost Concern	Farmer Maintenance Issue (%)	Farmer Govt Support Satisfactory	FS Maintenance Issues	FS Govt Support Satisfactory
Amroha	40 %	0	Yes	Yes	Yes
Bhagwanpura	40 %	0	Yes	Yes	Yes
Modhera	100 %	100	No	Yes	Yes
Baripatha	100 %	100	No	Yes	Yes

Discussion:

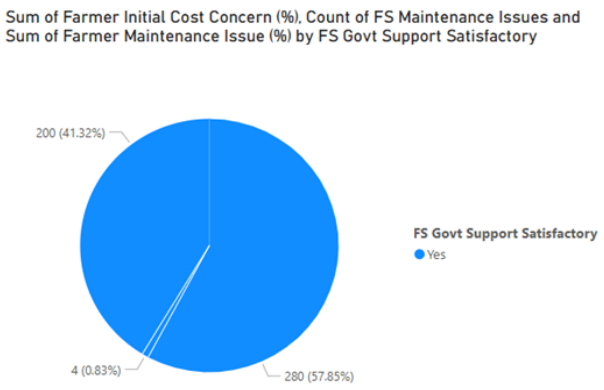
Limited access to subsidies and high initial investment were universal concerns. This affirms Rao & Shankar (2019), who highlighted that; marginalised farmers lack procedural and financial access to solar benefits.

Maintenance and Government Support

- Experience and Maintenance

- FS with >5 years of experience were present in all villages.
- FS from all states reported maintenance challenges, with Bhagwanpura and Amroha facing the highest frequency

Figure:3



Discussion:

System longevity and consistent service depend heavily on timely maintenance. Findings reflect national concerns raised by Li et al. (2022) on operational sustainability in decentralized solar systems.

Government Support

All 20 FS respondents confirmed receiving subsidies. However, they emphasized delays and inadequate monitoring.

Discussion:

This confirms the systemic difference in institutional support—while FSs, being state-appointed, receive benefits, farmers often remain under-supported due to structural exclusion.

Table: 5

Village	Farmer Initial Cost Concern	Farmer Maintenance Issue (%)	Farmer Govt Support Satisfactory	FS Maintenance Issues	FS Govt Support Satisfactory
Amroha	40 %	0	Yes	Yes	Yes
Bhagwanpura	40 %	0	Yes	Yes	Yes
Modhera	100 %	100	No	Yes	Yes
Baripatha	100 %	100	No	Yes	Yes

Public Health Outcomes

- Doctor Perspectives on Solar Electrification

From the 8 doctors:

- All confirmed reliable lighting post-solar installation.
- Modhera and Khurda district clinics were fully solar-functional.
- Doctors in Amroha and Bhagwanpura noted maintenance/inverter/battery issues, affecting regularity of various services (vaccine refrigeration and night-time services).
- **Discussion:**
  This aligns with WHO (2016), showing improved service capacity where solar works reliably. However, lack of long-term service contracts is a known bottleneck, as flagged in Smart Power India assessments.

Table 6:

Participant Type	Health Impact Observed (Direct)	Indirect IO
Farmers	No	Yes
Doctors	No	Yes
Farm Superintendents	No	No

- Indoor Environment & Women's Health

Farmers in Bhagwanpura and Modhera noted reduced indoor air pollution and improved well-being in solar-using homes, mainly due to solar lighting and cookstove adoption.

Discussion:

Public health benefits are clear but uneven. The effectiveness of solar interventions is closely tied to system reliability and user training, as reflected in GIZ (2021) findings.

Environmental Concerns and Policy Needs

- Environmental Awareness

- Across all respondent types, concern over groundwater depletion and solar waste was highest among FS.
- Farmers were least aware of long-term environmental implications.

Table:7

Participant Type	Energy Reliability	Lower Energy Cost	Govt Subsidy	Environmental Concern
Farmers	100	100	0	0
Farm Superintendents	100	100	100	100

Discussion:

This demonstrates a knowledge gap in solar literacy among users, emphasizing the need for environmental training and water-use education, especially where solar irrigation is involved.

- Training and Policy Improvement Needs

- Farmers in all villages requested better training and follow-up support post-installation.
- FS and doctors strongly recommended policy improvements focused on system maintenance and inclusive access.

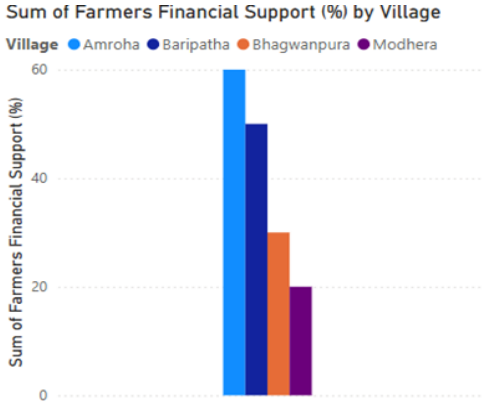
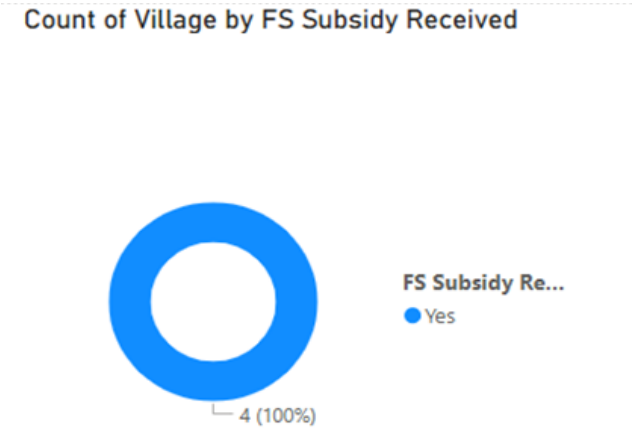
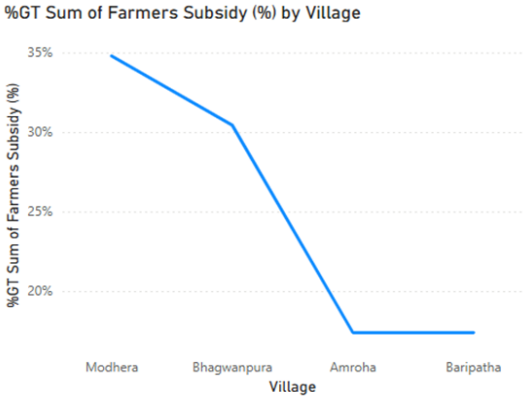


Figure:6



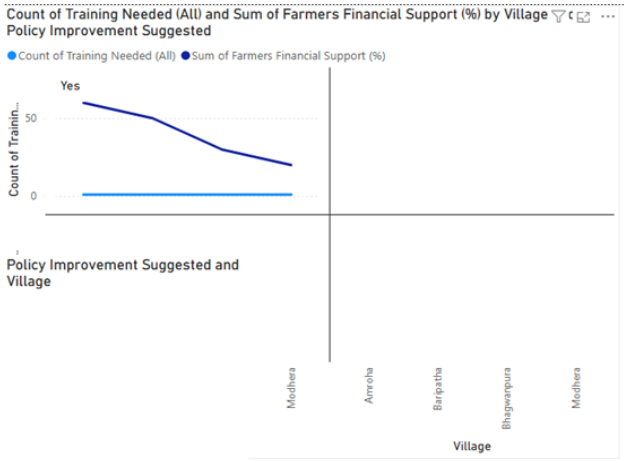
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Discussion:

Policy gaps highlighted by participants mirror national-level critiques by NITI Aayog (2020) and UNDP (2021), which call for integrated, user-centred program designs.

Figure: 8



Policy and Practice Implication

Introduction / Problem Statement

India's rural solar transition is accelerating, especially in agriculture, but lacks strategic planning. Unregulated pump use and poor site selection have led to groundwater depletion and inefficient deployment, threatening sustainability. With India aiming for 292 GW of solar capacity by 2030, it's important to plan where new installations go, so they support the environment as well as local needs..

Literature Review

Solar irrigation improves yields and reduces fossil fuel use (Shah, 2018; Kumar et al., 2020), while agrivoltaics boosts productivity. Yet, most tools lack integration with ecological data. Existing platforms like NIWE or RET Screen offer irradiance but ignore groundwater or health linkages—underscoring the need for a contextual, multi-layered approach.

Proposed Solution

I suggest developing a mapping tool that combines information about sunlight, land type, water levels, and existing infrastructure to find areas best suited for solar projects. It prioritizes both agricultural and health infrastructure.

Methodology

Data will be analyzed via QGIS, Python, and MCDA. A prototype will be piloted in Modhera, Amroha, and Neemuch, refined with stakeholder input for scalability.

Table: 7

Key Data Layers and Parameters

The proposed GIS model incorporates the following datasets:

Data Layer	Parameter Type	Source
Solar Irradiance	Energy potential	NIWE / NASA SSE
Groundwater Level	Resource vulnerability	Central Ground Water Board (CGWB)
Land Use / Land Cover (LULC)	Conflict potential	NRSC Bhuvan / Sentinel-2
Slope and Elevation	Suitability for panels	SRTM / ASTER
Agricultural Zones	Food-energy synergy	Ministry of Agriculture
Healthcare Infrastructure	Public service coverage	NRHM, MoHFW
Grid Proximity	Integration feasibility	REC / DISCOM datasets
Biodiversity Sensitivity	Environmental risk	ENVIS, MoEFCC
Population Density	Equity and access	Census of India

Advantages over Traditional Approaches

Conventional Methods	GIS-Based Planning
Based on policy quotas or irradiance only	Combines multiple environmental and social parameters
Uniform approach across regions	Region-specific, terrain-sensitive
High potential for land-use conflict	Avoids forests, wetlands, cultural or commons land
No integration with services	Aligns with water access, healthcare, infrastructure

Conclusion

Category	Key Findings
Technology Use	FS show greater diversity and duration in using solar tech than farmers.
Agricultural Effects	Productivity ↑ and water usage ↑; potential long-term sustainability issues.
Cost & Maintenance	High initial cost and lack of technical support hinder widespread satisfaction.
Health Impact	No direct health improvements observed by any group.
Policy Awareness & Equity	FS are highly aware and supported; farmer subsidies vary significantly.
Future Demands	Strong demand for financial aid, training, and improved solar policy delivery.

This paper has explored the inter-related impacts of solar technology on agriculture, public health, and the rural environment in India, drawing from both field and literature - based insights from four diverse villages. The findings demonstrates that while solar energy improves agricultural productivity and environment, enhances healthcare delivery, and promotes economic livelihoods, these gains are not evenly distributed. The challenges of inadequate system maintenance, groundwater overuse, gender and caste-based elimination, and fragile governance structures must be urgently addressed. If left unchecked, these issues threaten to undermine the sustainability and equity of India's solar energy transition. The research underscores the importance of treating solar energy not as a stand alone intervention but as a component within broader ecological and socio-economic systems. Through the Water-Energy-Food Nexus framework and inclusive governance mechanisms, it is possible to design solar policies that are both environmentally responsible and socially just.

The position advocated here is clear: solar technology, when deployed with foresight and inclusion, can be a powerful engine for sustainable rural transformation. However, this potential can only be realized through integrated policy frameworks, participatory planning, and ongoing institutional coordination.

Future studies should track how solar use affects groundwater over time, set up better systems for managing solar waste, and look at how local communities can play a stronger role in managing solar projects. As India continues to invest in its clean energy future, ensuring that this transition uplifts all sections of society must remain a central priority.

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Integrating Agrivoltaics in India for Carbon Sequestration and Carbon Credit Optimization

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Executive Summary

India has a critical choice between sustainable agriculture and climate mitigation on one hand and the demand for clean energy on the other. Agrivoltaics, a combination of solar photovoltaic (PV) power generation with agricultural crop cultivation, provides a multi-benefit solution addressing various problems such as land-use conflict, rural energy access, degrading soil health, and climate change. The current research investigates the possibility of adopting agrivoltaics systems in various agro-climatic zones of India, with an aim to maximize carbon sequestration and enhance economic viability through carbon credit generation. The study indicates that agrivoltaics systems make a considerable contribution to carbon emissions reduction, with the cumulative carbon sequestration potential as high as 2,100 tCO_2/ha/year in Rajasthan, Maharashtra, and Madhya Pradesh. This is thanks to the reduction of fossil fuel emissions from producing solar energy, increased soil organic carbon, and crop biomass above ground. The systems also increase soil health, maintain moisture in shaded places, and increase crop yield modestly based on crop type and system design. Economically, a typical 1 MWp agrivoltaics plant with fixed vertical bifacial panels on 1.91 hectares generates 15.76 lakh kWh/year, generating ₹55.18 lakh from power sales, ₹4.58 lakh from agricultural produce, and ₹12.14 lakh/year from carbon credits. This combination brings down the payback period from 7.47 years to 6.1 years, demonstrating the viability of the system. But large-scale adoption of agrivoltaics in India is hindered by large policy and regulatory hurdles. Land-use regulations in the majority of states necessitate the change of agricultural land to commercial for solar deployment, whereas PM-KUSUM does not have incentives designed specifically for agrivoltaics. The research suggests major reforms that would facilitate agrivoltaics implementation at scale, including agrivoltaics being a recognized agricultural land use, creating policy instruments, formulating technical guidelines, and launching training programs and financial incentives.

Context & Problem Statement

India is aiming to achieve net-zero carbon emissions by 2070 and provide food security to its growing population. The agriculture sector, a crucial livelihood for over 50% of the population, is a major greenhouse gas emitter. The mass installation of solar power infrastructure has led to land clearance and destruction of native ecosystems. Agrivoltaics, a synergistic land-use model that integrates solar photovoltaic (PV) installations with agriculture, has the potential to increase renewable energy capacity while sustaining agricultural productivity and environmental sustainability. However, agrivoltaics in India is under-explored due to little policy support, few pilot projects, and lack of awareness among farmers and stakeholders. This study fills a critical knowledge gap in the integrated use of agrivoltaics systems in India, particularly in terms of their environmental advantages, such as carbon sequestration. India's carbon market is still maturing, and farmers are not aware of the channels through which agrivoltaics can earn money through carbon credits. Socio-economic barriers, landholding concerns, and knowledge deficiencies also hinder large-scale deployment. Responding to these challenges, the following **research questions** inform this study:

1) How can agrivoltaics benefit farm and solar energy in India?

2) What amount of carbon can agrivoltaics remove in various regions of India?

3) How can farmers make money through carbon credits from agrivoltaics?

4) What policy and regulatory mechanisms are required to facilitate large-scale adoption of agrivoltaics in India?

5) What are the socio-economic advantages and challenges to farmers adopting agrivoltaics systems in India?

Research Objectives:

- Quantify the Carbon Sequestration Potential: Evaluate and quantify the carbon sequestration capacity of agrivoltaics systems across diverse agro-climatic regions in India.
- Assess Agronomic and Environmental Co-benefits: Investigate the impacts of agrivoltaics on soil health, crop yield, water retention, and biodiversity enhancement, to understand their role in promoting sustainable agricultural practices.
- Evaluate Financial Viability and Carbon Revenue Potential: Analyze costs, returns, and carbon credit revenue potential for agrivoltaics systems.
- Analyze Policy and Institutional Frameworks: Review existing policies, incentives, and regulatory frameworks relevant to agrivoltaics in India and policy recommendations to support large-scale deployment.

Literature Review

With increasing energy requirements and decreasing arable land, combining solar panels with agriculture has twin benefits: power generation and sustained agricultural productivity (Goetzberger & Zastrow, 1982; Barron-Gafford et al., 2019). In India's diverse climates, pilot projects such as those in Maharashtra have demonstrated how elevated PV installations over crops like grapes can yield both electricity and harvests, while reducing irrigation costs (Kulkarni et al., 2023). Agrivoltaics not only mitigate land-use conflict but also optimize resource efficiency. For instance, solar panels can reduce crop heat stress and soil evaporation, lowering water use by 10–30% (Marrou et al., 2013). In Jodhpur, a 100 kW agrivoltaics system supported legumes and pulses with only 5–12% yield reduction while producing ~125 MWh annually (Ramachandra et al., 2021). Such minor yield impacts are often offset by energy revenues (Adeh et al., 2018).

Elevated-panel designs support high-value vegetables and fodder, maintaining or improving soil fertility and biodiversity (Dinesh & Pearce, 2016; Weselek et al., 2019). Native vegetation or cover crops beneath panels enhance soil organic carbon and ecosystem health. India aims to install 270–300 GW of solar capacity by 2030 (MNRE, 2023). Agrivoltaics can reduce pressure on land while supporting these goals. Each MW of agrivoltaics PV can produce 1.25 GWh/year, displacing 500–700 t CO_2 based on India's grid emission factors (~0.5–0.7 t CO_2/MWh) (CEA, 2023; Sharma & Goel, 2020). India's 25 million diesel pumps emit ~15.4 Mt CO_2/year, and replacing them with solar especially agrivoltaics solar could cut 45–62 Mt CO_2 annually (TERI, 2021).

Carbon sequestration further enhances agrivoltaics' climate benefits. Crops and native grasses grown under panels store more carbon in biomass and soils, especially with deep-rooted or leguminous species (Wells et al., 2021). India's cropland sequestration potential is estimated at 143–180 Mt CO_2/year (Venkatesh et al., 2019). Agrivoltaics could contribute substantially, with an estimated 1– 5 t CO_2/ha/year captured in biomass and soil. Carbon markets add financial incentives. The Verified Carbon Standard VM0042 allows credits for soil carbon gains and emission reductions (Verra, 2023).

With India's Carbon Credit Trading Scheme (CCTS) and a voluntary offset market launching by 2025 (MoEFCC, 2023), farmers can monetize carbon savings. For example, sequestering 5 t CO_2e/ha/year could yield $50–100/ha/year at voluntary market rates (ICAP, 2023). Agrivoltaics farmers may also benefit from energy incentives such as the KUSUM scheme, which

supports solar pump installations (MNRE, 2022).

Research Focus and Methodology

The study explores the integration of agrivoltaics in India to enhance carbon sequestration and optimize carbon credit. It aims to meet India's NDCs and transition to a low-carbon economy by integrating photovoltaic panels with agricultural practices. The research aims to quantify carbon sequestration potential, assess agronomic and ecological benefits, evaluate financial viability, and recommend enabling frameworks for national-scale implementation. The mixed- methods approach uses quantitative geospatial modelling, literature and secondary data

analysis, field-based insights, and qualitative policy assessment to address both environmental and economic dimensions of agrivoltaics systems.

1) Data Sources and Literature Review: The study will initiate with an extensive literature review of global and Indian agrivoltaics systems, drawing from peer-reviewed journals, Secondary datasets will be sourced from:

- ISRO-Bhuvan and Bhoonidhi portal for remote sensing data (NDVI, NDWI, land use, solar radiation)
- ICAR and FAO for soil and crop parameters
- Verra's VM0042 methodology and IPCC Tier 1/2 Guidelines for carbon accounting
- India's Carbon Credit Trading Scheme (CCTS) and KUSUM scheme policy documents for national carbon finance alignment.

2) Carbon Sequestration and Environmental Impact Assessment: Carbon sequestration potential will be estimated using OpenLCA software, integrated with soil organic carbon (SOC) and biomass coefficients from literature and global databases. Environmental and agronomic parameters such as soil fertility, crop yield, and vegetative biodiversity will be reviewed based on prior field trials and case studies.

3) Policy and Gap Analysis: A qualitative content analysis will be conducted on national and sub-national policies particularly India's CCTS, KUSUM, and agri-renewable energy programs. International frameworks (e.g., EU and US agri-C programs) will be compared for policy benchmarking.

Carbon Sequestration Potential of Agrivoltaics Systems in India:

Agrivoltaics are most effective in regions with high sunlight, expansive farmland, and water scarcity, such as Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Andhra Pradesh/Telangana, Karnataka, and Tamil Nadu. These regions have vast wheat, pulse, and cotton fields, which can be utilized for PV. Haryana and Punjab, with their intensive cropping and rich soil, face seasonal water deficiency and smog issues. Kharif and Rabi crops dominate, while fallow and wastelands offer high potential without displacing agriculture.

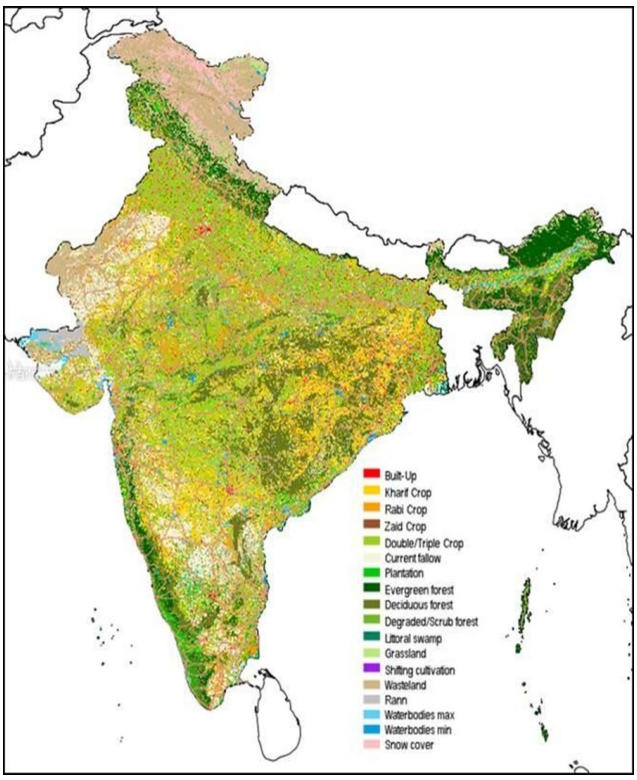


Fig 1: LULC Map of India (ISRO)

Quantifying Carbon Sequestration in Agrivoltaics:

Three elements are involved in quantifying agrivoltaics carbon: (1) carbon sequestered in the soil, (2) carbon in above-ground biomass, and (3) avoided fossil CO_2 due to the solar energy generated.

The graph shows that Rajasthan leads in agrivoltaics CO_2 sequestration at 2100 $tCO_2/ha \cdot yr$, followed by Maharashtra and Madhya Pradesh (2000 $tCO_2/ha \cdot yr$). The largest share comes from avoided CO_2 emissions (1000

–1100 tCO_2/ha·yr), while soil and biomass CO_2 contribute 50–100 tCO_2/ha·yr combined. States like Kerala and Odisha show lower potential (1800 tCO_2/ha·yr) due to less solar irradiance.

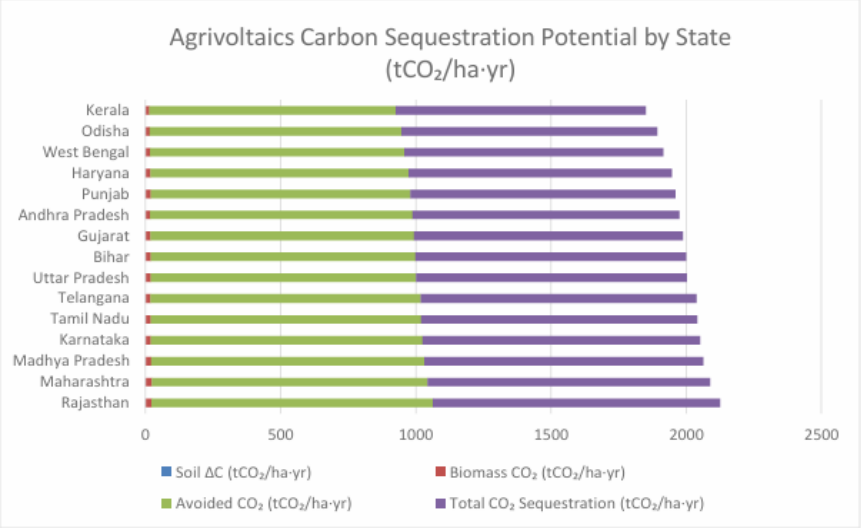


Table 2: Selection of crops based on structure height and available sunlight

Sunlight Requirement	Daily Light Integral (DLI)	Solar Radiation (kWh/m²/day)	Cultivation Months	Crop Height Category (cm)	Crop Examples
Low Light Crops	3–6 mol/m²/day	0.41–0.83	Sept–Feb	A (≤50)	*Centella asiatica (Brahmi)*
			March–Aug	C (≤150)	*Arrowroot*
				B (≤100)	*Himalayan Muhroom (Gucchi)*
			All months	D (≤200)	*Coffee (shrub)*
High Light Crops	12–18 mol/m²/day	1.66–2.48	Sept–Feb	A–C (≤150)	*Black Gram, Cabbage, Lettuce, Spinach, Onion,*
					Rye, Coriander, Fenugreek, Garlic, Potato, Mint, Tobacco, Wheat
				E–F (>150)	*Snake Gourd, Bitter Gourd*
			March–Aug	A–C (≤150)	*Lettuce, Spinach, Onion, Chili, Eggplant, Stevia, Coriander, Garlic, Rye, Sesame*
				D–F (>150)	*Snake Gourd, Bitter Gourd, Indian Bean, Ash Gourd, Pearl Millet (Bajra), Guava Hybrid*
Very High Light Crops	>18 mol/m²/day	>2.48	Sept–Feb	A–C (≤150)	*Poppy, Pumpkin, Watermelon*
				D–E (≤300)	*Maize, Bottle Gourd*
			March–Aug	A–C (≤150)	*Pumpkin, Watermelon, Zucchini*
				D–E (≤300)	*Paddy, Maize, Blonde Cucumber, Bottle Gourd*
			All months	A–B (≤100)	*Geranium*

Component	Description	Formula Used
Soil Organic Carbon (SOC)	Carbon stored in soil through organic matter accumulation (crop residues, reduced erosion, microbial activity)	ΔSOC (tC/ha) × (44/12)
Biomass Carbon (Above-Ground)	Carbon fixed in plant biomass (shoots and roots) during crop growth. Contributes to carbon pool if residues are returned to soil or left as cover.	yield_dry × 0.5 × (44/12)
Avoided Fossil CO_2	CO_2 emissions avoided by replacing grid electricity (mainly coal-based) with solar power generated by agrivoltaics PV panels.	E_solar × EF_grid(1,500 MWh × 0.713 tCO_2/MWh)

Assessing Agronomic and Environmental Benefits of Agrivoltaics Systems in India

In India, where arable land and water are scarce resources, Agri-PV provides a sustainable solution that can improve soil health, support biodiversity, enhance crop yield and water use efficiency while generating renewable energy.

1. Soil Health

Agri-PV technology, which integrates photovoltaic panels with agricultural land, offers potential benefits for renewable energy production and sustainable agriculture. It improves soil health, increasing moisture by 33%, microbial biomass by 30%, and soil organic carbon by 7.9%. This enhances water-holding capacity and carbon sequestration, while decreasing soil pH by 4.4%.

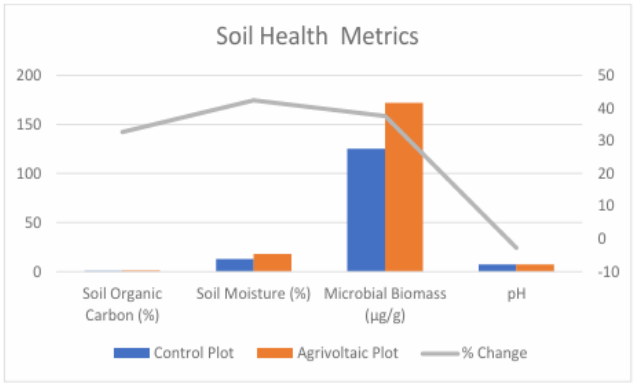


Fig 3: Soil health metrics

2. Biodiversity Impact:

Agri-PV systems, which integrate solar panels with farming land, are becoming sustainable options for clean energy, food, and biodiversity conservation. These systems increase ecological diversity, with a 71% increase in insects, 37.5% increase in pollinator species, and 117% increase in native vegetation. The Shannon Diversity Index shows a 50% increase, indicating a more diverse and balanced community.

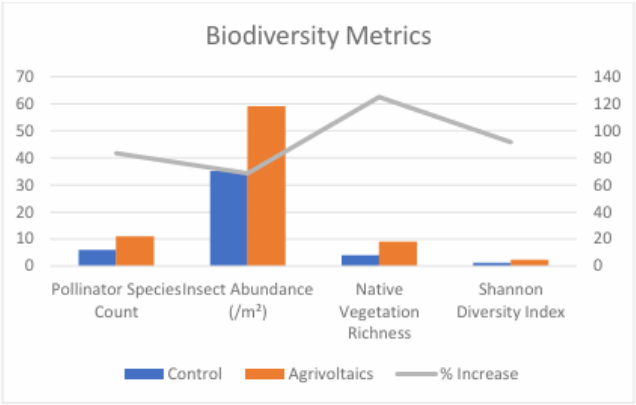


Fig 4: Biodiversity metrics

3. Crop Yield Improvement

Agri-PV systems with crops grown under solar panels are gaining popularity due to concerns about potential yield reduction due to less sunlight. However, recent evidence shows most crops perform well or even better under partial shade. Spinach, Tomato, Chilli, and Turmeric show increased yields under Agri-PV conditions, while Wheat, Black Gram, and Mustard show slight declines. Tomato yields are boosted by 19% due to solar panel shading, while turmeric shows a 16% increase due to cooler microclimate.

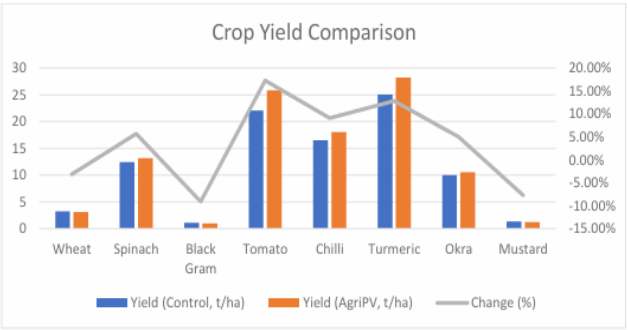


Fig 5: Crop Yield Comparison

4. Water Use Efficiency

Indian agriculture faces water scarcity, with open-field farming contributing to high evapotranspiration and inefficiency. Agri-PV systems offer renewable energy and water efficiency, reducing water usage by 30% and irrigation frequency by 40%. Crops like tomatoes, leafy greens, and turmeric can sustain higher yields with less water, promoting sustainability in arid and semi-arid areas.

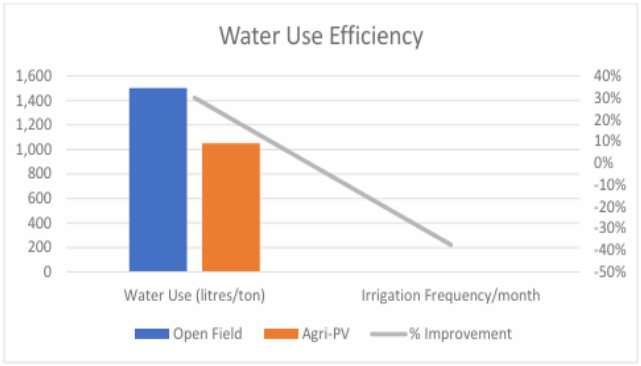


Fig 6: Water Use Efficiency

Financial Viability of Agrivoltaics in India with Carbon Credit Optimization

1. Crop selection

Agrivoltaics is best suited with sun- or shade-tolerant crops. Indian pilots have observed that leafy greens, millets (e.g. sorghum), and medicinal/herb crops grow well under partial shading. Other possibilities are gourds (pumpkins, squash), chili peppers, okra, cabbages, garlic/onion, and spice crops (turmeric, pepper, coffee). Taller panels enable inter-row crops below; e.g. chili, tomato or spinach could thrive. Principal cereals such as rice or wheat are less proven under APV. Farmers may select an appropriate high-value crop combination.

2. Cost-Benefit Analysis (for Vertically Installed System – 1 MWp)

For agrivoltaics, the 1 MWp (Megawatt-peak) system is widely utilized as the reference unit for techno-economic assessment, policy modelling, and pilot-scale deployment in India. It offers a scalable and realistic reference point to measure land, energy, and revenue outputs. For a 1 MWp agrivoltaics system with a fixed vertical 2×10 bifacial module design, 1.91 hectares of land area is necessary, owing to engineering limitations like 7.6- meter interrow spacing, safety clearances, and tractor or irrigation access. This design maximizes capture of solar irradiance by both sides of the bifacial panels and adequate photosynthetically active radiation (PAR) for plant growth.

Table 3: Optimal Crop Combination

Structure Type and Table Size	Inter-row Gap (m)	Field Area (ha)	Light Requirement	Crop Height (cm)	Crop Combination (Best Mix)	Cultivation Months	Yield Income /ha (₹)	Carbon Sequestration (tCO_2/ha/year)
Fixed tilt 2×10 modules/table	4	1.22	Medium–High	≤150 cm	Tomato + Spinach + Okra	March–Sept	₹2,10,000	3.8
Fixed tilt 1×10 modules/table	4	1.74	High–Very High	≤200 cm	Maize + Bitter + Gourd + Lettuce	June–Oct	₹2,35,000	4.1
Single axis tracking (80 modules/tracker)	4	1.75	Very High	≤300 cm	Paddy + Maize + Pumpkin	July – Nov	₹2,50,000	4.5
Vertically installed 2×10 modules/table (bifacial)	7.6	1.91	High–Medium	≤150 cm	Aloe Vera + Garlic + Stevia	All year	₹2,40,000	5

Table 4: Layout Needs for 1 MWp Across Structures

Structure Type	Interrow Gap (m)	Area Needed (ha)
Fixed tilt 2×10 modules (standard)	4.0	1.22
Fixed tilt 1×10 modules	4.0	1.74
Single-axis tracking	4.0	1.75
Fixed vertical 2×10 bifacial (your case)	**7.6**	**1.91**

Financial analysis:

- Location: India (Avg irradiation = 5.5–6.0 kWh/m²/day)
- Field area: 1.91 ha
- System: Fixed vertical 2x10 bifacial
- CUF: 18%
- PV cost: ₹4 Cr/MW
- Crop revenue: ₹2,40,000/ha/year

Table 5: Financial analysis

Cost Component	Formula	Value (₹)
PV System CapEx	1 MW × ₹4 Cr	₹4,00,00,000
Agriculture CapEx	₹80,000 × 1.91 ha	₹1,52,800
Total Initial Cost	PV + Agri CapEx	₹4,01,52,800
Energy Generation	1,000 kW × CUF × 8760 = 15,76,800 kWh	15.76 lakh kWh/year
Energy Revenue	15.76 lakh × ₹3.5	₹55,18,000/year
Crop Revenue	₹2.4 lakh × 1.91 ha	₹4,58,400/year
O&M Cost	1.5% of CapEx	₹6,02,292/year
Net Annual Revenue	Energy + Crop – O&M	₹53,74,108/year
Simple Payback Period	Total Cost / Net Revenue	7.47 years

3. Carbon Credit Revenue Estimation

The carbon credit revenue arises from two main sources: avoided carbon emissions due to solar energy replacing fossil fuels, and soil/crop-based sequestration from agricultural practices under solar installations (Table 6).

4. Revised Payback Period with Carbon Credit

Including carbon credit revenue improves the financial viability of agrivoltaics systems. Below is a comparative payback analysis that includes both the net annual revenue from electricity and additional revenue from carbon credits.

Table 6: Carbon Offset and Revenue Estimation

Component	Formula	Result
Avoided CO_2 (solar energy)	15,76,800 kWh × 0.85 kg CO_2/kWh	13,40,280 kg CO_2/year ≈ 1340.28 tCO_2/year
Soil and Crop Sequestration	1.91 ha × 5.0 tCO_2/ha/year	9.55 tCO_2/year
Total Carbon Offset	1340.28 + 9.55	1349.83 tCO_2/year
Carbon Credit Revenue	1349.83 × ₹900/tCO_2	₹12,14,847/year

Table 7: Payback Period Estimation with Carbon Credits

Description	Value (₹)
Net Annual Revenue (without carbon)	₹53,74,108
Carbon Credit Revenue	₹12,14,847
Total Annual Benefit	₹65,88,955
Capital Cost	₹4.01 crore
Revised Payback Period	6.1 years

5. Recommendations for Agrivoltaics in India

The performance of agrivoltaics varies based on the crop mix and solar structure. The following recommendations are based on maximizing revenue, carbon offsets, and system utilization:

Table 8: Optimal Agrivoltaics Crop–Structure Combinations

Criteria	Best Crop Combination	Recommended Structure Type
Maximum Economic Return	Aloe Vera + Garlic + Stevia	Vertically installed bifacial panels
Highest Carbon Credit Yield	Maize + Paddy + Bitter Gourd	Single-axis tracking system
Shortest Payback Period	Tomato + Okra + Spinach	Fixed tilt (2×10 module structure)
Year-Round Operation	Aloe Vera + Stevia (perennials)	Any fixed tilt or bifacial structure

Policy Frameworks and Strategies for Agrivoltaics in India

India's policy climate for agrivoltaics is currently limited and disjointed. The PM-KUSUM program, initiated in 2019, favors 10 GW of decentralized solar over agricultural land, but focuses mainly on barren or non-cultivable land. While guidelines include solar on stilts over crops, higher expenses and lack of premium tariffs lead to little adoption of genuine agrivoltaics layouts. Renewable Purchase Obligations and tariff structures do not have agrivoltaics-specific arrangements. Land-use regulations are a major impediment, with most states demanding land- use conversion from agricultural to commercial for solar installation. There is no central legislation to define or safeguard agrivoltaics under existing land or electricity acts. The Carbon Credit Trading Scheme (CCTS) and Green Credit Rules signal an official shift towards domestic carbon markets. However, agrivoltaics is not directly mentioned in the framework for a voluntary carbon market in agriculture.

Table 10: State-Level Policies and Schemes

State	Scheme / Policy	Key Features
Delhi (NCT)	Mukhyamantri Kisan Aay Badhotri Yojana	Raised solar structures on farmland; ~₹8,333/acre/month lease; RESCO model; uninterrupted farming beneath panels.
Gujarat	Suryashakti Kisan Yojana (SKY)	₹7/kWh tariff (₹3.5 state + ₹3.5 utility) for 7 years; ₹3.5/kWh afterward; farm/barren land eligible; supports farmer income.
Karnataka	Surya Raitha Scheme	Solar pumps on farmland; 2/3 power for irrigation; excess sold to grid at ₹7.50/kWh; indirectly promotes elevated panels.
Maharashtra	Mukhyamantri Saur Krushi Vahini Yojana (via EESL)	100 MW farm solar under KUSUM; ₹3.11/kWh tariff for 25 years; state issued 2017 Agri-PV guidelines with tall structures.
Odisha	Annual Lease Model (Pilot)	25-year land lease; ₹20,000/acre/year to farmers; farmers retain cultivation rights explicit dual-use agrivoltaics model.
Rajasthan	KUSUM Component A + Solar Policy 2019	Projects allowed only on barren land excludes cultivated land, limiting agrivoltaics.
Haryana	KUSUM Component A	Active in solar pump tenders, but no mention of dual- use farming or elevated panels.
Uttar Pradesh	KUSUM A Implementation	Land policy restricts projects to arid or uncultivable land, sidelining agrivoltaics potential on cropland.

Table 11: Policy Gaps and Barriers

Policy Barrier	Description
1. Land Use Restrictions	Agricultural land is classified for farming only; using it for solar requires land-use conversion, often to "industrial" or "commercial."
2. No Dedicated Agrivoltaics Incentives	KUSUM, RPOs, RECs treat agrivoltaics and standard PV the same. No premium tariffs for APV despite higher cost of raised structures and yield trade-offs.
3. Lack of Technical Standards	No national guidelines on panel height, crop compatibility, row spacing, or soil health. Project design left to developers.
4. Water Rights Uncertainty	Model Ground Water Bill (2016) omits explicit water rights for APV. APV may require water for crops and panel cleaning.
5. Grid Connectivity & Evacuation Costs	Farmers often must pay for evacuation infrastructure (feeders, substation upgrades). In rural areas, substations often lack capacity.

6. Carbon Credit Integration Gap	Agrivoltaics has multiple climate co-benefits (sequestration, avoided emissions), but no framework recognizes these for carbon credits.
7. Lack of R&D & Pilot Scaling Support	Limited central R&D budget or coordination for APV innovation; pilots remain fragmented across states.

Table 12: International Agrivoltaics Policy Models and Lessons for India

Country	Policy/ Program	Key Features	Relevance to India
Germany	EEG Feed-in Tariff & "Solarpaket I" (2024)	Special auction category for "special solar plants" (agrivoltaics, floating PV, etc.) Higher bid caps and FIT bonuses for Agri-PV- Technical criteria to ensure dual-use compliance	India can create dedicated agrivoltaics auctions or tariff premiums under KUSUM or new programs introduce technical benchmarks (e.g. panel height, spacing) to ensure food- energy co-benefits
Japan	Agricultural Land Act and FITs	Agri-PV allowed on farmland with strict rules: min panel height, crop yield ≥70%- Revised law (2021–24): farming must continue or FIT is revoked 342 APV projects suspended in Aug 2024 for violations	India should define panel placement, yield criteria, and enforcement rules Allow conditional solar use of farmland without full land conversion
United States	Federal and State Programs	Agrivoltaics Research & Demonstration Act (2023): USDA-led definitions and pilots- Some states mandate co-location or preservation of farmland (e.g., "smart solar" zoning) USDA REAP grants support APV adoption	India can replicate via ICAR- led Agri-PV pilots; integrate agrivoltaics in rural or agricultural schemes States can embed "smart solar" ideas in land zoning and RPOs Ministries of Agriculture and MNRE should jointly promote agrivoltaics in farm finance and rural support policies

Recommendations: To scale agrivoltaics, India needs to first categorize it under agricultural land use, revising state land legislation to prevent expensive reclassification. Water rights need to be established through revising the Model Ground Water Bill (2016). Implement APV- specific tariffs and recognition of green credits, and enhance KUSUM with exclusive agrivoltaics auctions. Make eligibility for carbon credits under the Carbon Credit Trading Scheme (2023) using APV methodologies. Release national technical guidelines (panel height>2.2 m, compatibility with crops) for Indian regions. Foster RESCO/shared PPA schemes to reduce farmer risk, and provide subsidized insurance and loans under PM-Kisan. Establish local capacity building by incorporating APV into KVK and rural energy training programs.

Identify best zones using GIS mapping and incorporate agrivoltaics into state RPO and solar policies. Promote biodiversity-supportive designs (e.g., legumes, native grasses), and create a monitoring system to monitor performance and provide feedback for adaptive policy adjustments.

Conclusion

This research verifies that agrivoltaics can be a revolutionizing strategy for India in synergistically meeting renewable energy targets, farm productivity, and climate resilience.

Results show that major states such as Rajasthan and Maharashtra can sequester as much as 2,100 tCO_2/ha/year, of which more than 1,100 tCO_2/ha/year comes from reduced fossil emissions, and further carbon accumulated in soil and crop biomass (50–100 tCO_2/ha/year). A 1 MWp agrivoltaics farm on 1.91 ha provides a gross annual revenue of ₹65.88 lakh, integrating energy sales, crop income, and ₹12.14 lakh as carbon credits, bringing down payback from 7.47 to 6.1 years. Ideal crop structure models such as Aloe Vera + Stevia (round-the-year income), Maize + Paddy (carbon credits), and Tomato + Spinach (short payback) are found to be versatile in various Agro-climatic zones. But major challenges still remain land-use conversion barriers, absence of agrivoltaics-specific tariffs or carbon credit entitlement, and lack of national design guidelines. In order to scale agrivoltaics, India will need to define agrivoltaics as agricultural land use, implement APV-specific tariffs and carbon credit regimes, and issue technical guidelines on panel design and crop choice. The experiences from nations such as Japan and Germany indicate that unequivocal dual-use regulations, tax incentives, and effective enforcement systems are imperative. With policy reforms integrated and financial instruments, agrivoltaics can emerge as a key pillar of India's rural development and net-zero strategy.

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Consumer and Producer Perspectives on Circular Economy Transition in Indian Textile Industry

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Executive Summary

The global textile industry, while economically significant, is a major cause of environmental degradation, counting for 10% of global carbon emissions and 20% of wastewater production. In India, the sector is vital, contributing 2% to the national GDP and employing over 45 million people. However, the industry's prevailing Linear Economy (LE) model cantered on mass production, Over-consumption, and irresponsible disposal has led to massive water use, greenhouse gas emissions, resource depletion and escalating textile pollution problem. Despite this, Circular Economy (CE) principles which advocate for sustainable production and consumption, it has seen limited implementation in India. This research explores the barriers and potential for CE integration within India's textile sector using a mixed-methods approach including literature analysis, stakeholder surveys, and interviews. Key objectives include identifying awareness levels, adoption barriers, and opportunities for circular practices among manufacturers, retailers, and consumers.

The study finds growing awareness of sustainability among stakeholders, particularly regarding environmental damage from water-intensive dyeing processes and landfill issues. However, systemic barriers such as complex supply chains, inadequate regulation, lack of technological access, and limited consumer engagement continue to hinder CE adoption. High initial costs and weak incentives also deter businesses from shifting to circular models. The findings underscore the urgent need for policy support, financial incentives, education, and infrastructure development to facilitate a circular transition. This research advocates a clear position: a systemic shift to Circular Economy practices in India's textile industry is not only feasible but essential to achieve environmental sustainability and socio-economic resilience of the sector.

Context & Problem Statement

The Indian fashion and textile industry, a cornerstone of the national economy employing over 45 million people and contributing around 2% to the GDP, is facing a mounting sustainability crisis. As the third-largest textile producer globally, India's sector is marked by a resource-intensive, linear production model that results in significant environmental degradation.

This model drives excessive water consumption (up to 200 liters per kilogram of fabric), high carbon emissions, and the generation of approximately 1 million tons of textile waste annually, of which only 20–25% is being reused or recycled. The environmental footprint extends from toxic dyeing processes to disposal of post-consumer clothing in land-fills often in low-income regions, exacerbating both ecological and social burdens. The urgency of addressing this issue is underscored by the global and local consequences of the current fashion system. In India, the sector's rapid growth, fuelled by fast fashion and rising consumer demand, has intensified pressures on water resources (almost all major rivers have at least one textile hub in its proximity and major source of its pollution), and led to unsustainable waste management practices.

The stakes are high: unchecked, the linear model threatens India's environmental security, public health, and the livelihoods of millions. Conversely, transitioning to sustainable practices could yield substantial benefits, including a 25-30% reduction in sectoral emissions, up to 50% less water consumption, and the creation of lakhs of green jobs.

Despite the promise of the Circular Economy (CE) paradigm which prioritizes waste minimization, resource efficiency, and material circularity adoption in India's textile sector remains nascent.

Literature Review

The Circular Economy (CE) has emerged as a transformative paradigm for rethinking production and consumption, especially within resource-intensive sectors such as textiles. Defined by the Ellen MacArthur Foundation (2012) as a regenerative system that designs out waste, prolongs product life, and closes material loops, is estimated to generate $560 billion in global annual savings by 2030 through resource efficiency and reduced emissions (Ellen MacArthur Foundation, 2017). Scholars widely regard CE as a pathway to decouple economic growth from environmental degradation. However, as Kirchherr et al. (2018) emphasize, CE implementation often remains superficial unless accompanied by deep institutional, cultural, and systemic transformations.

In the textile industry, CE aligns closely with design-led interventions such as slow fashion (Gwilt, 2014) and emotional durability (Chapman, 2009), which promote product longevity and reduce consumption cycles. Circular business models like rental, resale product-as-a-service have gained global momentum (Bocken et al., 2016; Pal, 2017) yet their scalability in India is hindered by infrastructural limitations and affordability concerns..

India's textile and apparel sector contributing 12% to exports and 13% to industrial production, illustrates both the urgency and potential for circular transformation. Despite the presence of recycling hubs like Panipat, studies reveal that only 20–25% of textile waste in India is recovered annually (Narayanaswamy et al., 2022).

Technological innovations such as blockchain and IoT can enable traceability and reverse logistics (KPMG India, 2019), but adoption remains low in MSME clusters due to financial and knowledge constraints.

Zero Liquid Discharge (ZLD) technologies demonstrate environmental potential (GIZ, 2014) but remain cost-prohibitive without supportive policy ecosystems. Moreover, CE policies in India remain fragmented. While schemes like the Technology Upgradation Fund Scheme (TUFS) target energy efficiency, they lack enforceable circularity mandates. A comparative policy analysis reveals that, unlike the European Union's Extended Producer Responsibility (EPR) mandates and standardized metrics, India's policy landscape relies on vague notions of "sustainability" and "recycling."

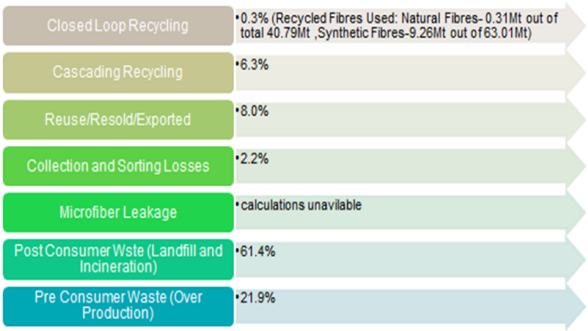


Figure 3: Total Textile Waste Categories and their Percentages

Data Source: CGR 2024 (Circularity Gap Report Dashboard)

Three conceptual debates dominate the literature: Balancing industrial scale with artisanal traditions like handloom and upcycling (Chapman, 2009), the challenge of integrating automated technologies into informal waste economies, and the consumer behavior gap despite 85% of surveyed Indian consumers expressing willingness to pay for sustainable fashion, fast fashion remains dominant (Pal, 2017).

The literature reveals several critical gaps:

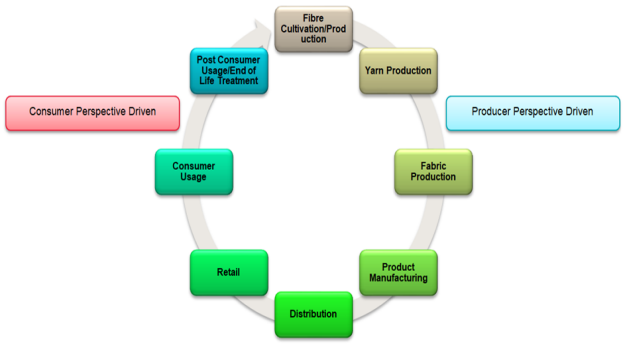
- **Fragmented Evidence on Consumer-Producer Feedback:** Limited research exists on how design-for-disassembly, mono-material designing and consumer engagement can close the loop in textile value chains.

- **Underrepresentation of MSMEs and Rural Clusters:** Most research and interventions focus on large, urban manufacturers, neglecting the vast network of micro, small, and medium enterprises (MSMEs) and rural producers who form the backbone of Indian textiles.
- **Lack of Standardized Metrics and Data:** The absence of robust, standardized circularity metrics and real-time monitoring systems hampers the ability to measure progress and impact.

This research tries to address these gaps by investigating the potential for CE integration in the Indian textile sector by focusing on both producer and consumer perspectives in Textile supply chain (both upstream & downstream) as both stakeholders play critical role in ensuring the success of CE initiatives.

Figure: Complete Lifecycle of a Circular Fashion Product covering Downstream & Upstream

The study aims to illuminate barriers such as high capital costs attached with CE models, technological limitations, and behavioral inertia of consumers, and propose possible pathways to overcome these barriers.



RESEARCH FOCUS

This research aims to:

- Evaluate current practices and challenges in embedding CE within India's textile sector.
- Identify drivers and barriers among stakeholders across the value chain.
- Develop actionable strategies for policymakers, industry stakeholders, and consumers.

METHODOLOGY

This position paper adopts a mixed-methods approach combining quantitative surveys and qualitative interviews to gain a comprehensive understanding of circularity adoption across India's textile and fashion ecosystem. The research design was structured to examine perspectives from both producers and consumers through SPSS study of questionnaires, also integrating qualitative analysis of expert interviews.

1. Producer Questionnaire

A structured questionnaire was circulated among over 90 stakeholders from various segments of the fashion production supply chain, including merchandising managers, production heads, designers, and brand owners. Participants were approached via LinkedIn, WhatsApp, and email, with a final sample of 39 valid responses.

Prior to survey distribution, participants were informed about the purpose of the study, assured of confidentiality, and provided consent to participate. The questionnaire focused on practical challenges and readiness for circular economy in areas: Design, Sourcing, Manufacturing, and Post-consumer Waste Management.

2. Consumer Behavior Questionnaire

To assess consumer engagement with circular fashion, a separate questionnaire was disseminated through online platforms and sustainability-focused communities, targeting individuals with a basic understanding of sustainability. The survey received 78 responses from a pool of 300+ fashion consumers. The instrument measured five key behavioural dimensions: Awareness & Attitude, Purchasing Behaviour, Usage & Care, End-of-Life Management and Future Perspective. Ethical considerations were maintained through informed consent and data anonymity declarations embedded in the Google Form.

3. Semi-Structured Interviews

To complement the survey data, three semi-structured interviews were conducted with: A Merchandising Manager from a textile export house

- The Founder of a Sustainable Fashion Brand (Rachna Swarup, B77)
- A Sustainable Fashion Influencer and Consumer (Tanishka Mishra)

Each interview followed a flexible guide designed to probe key themes such as supply chain fragmentation, consumer perception of sustainability, circular design practices, market barriers, and the role of MSMEs. Interviews were conducted virtually, recorded with participant consent, and later thematically analyzed to extract qualitative insights that enrich and contextualize the survey findings.

KEY FINDINGS AND CENTRAL ARGUMENT

Consumer Study Insights:

- ***Awareness vs. Accessibility Gap:*** Consumers, particularly urban, are aware of sustainability but face limited access to circular fashion options in Tier 2 and Tier 3 cities.
- ***Greenwashing and Lack of Clarity:*** Consumers find it challenging to differentiate genuine sustainability efforts from deceptive marketing.
- ***Cultural Mind-sets and Fashion Attachment:*** Emotional and cultural ties to garments in Indian households' support reuse and gifting, but young consumers often associate second-hand clothing with lower status and lack of fashion appeal.
- ***Lack of Consumer-Centric Circular Models:*** Circular initiatives tend to be brand-driven rather than consumer-inclusive, requiring more community-focused, engaging models like repair hubs and up cycling workshops.
- ***High Price Points as a Barrier:*** The premium cost of sustainable fashion discourages mass adoption, especially price-sensitive youth.
- ***Fragmented Return and Repair Infrastructure:*** Return policies are often unclear or logistically inefficient, deterring consumers from participating repeatedly in circular initiatives.

Producer Study Insights:

- ***Supply Chain Fragmentation and Lack of Standardization:*** Indian textile supply chain operates in silos with no uniform sustainability standards, leading to inconsistent practices and data gaps.
- ***Resistance and Cost Constraints among Suppliers:*** Tier 2 and Tier 3 suppliers often lack awareness, resources and incentives to adopt circular practices, compounded by higher costs of sustainable materials.
- ***Challenges in Traceability and Data Transparency:*** Full visibility of environmental impact from raw materials to finished products remains difficult due to limited data sharing and fragmented supply systems.
- ***Design Constraints for Circularity:*** Designing for recyclability or disassembly often restricts creativity and aesthetics, balancing fashion with sustainability remains a challenge.
- ***High Costs and Certification Overload:*** Eco-friendly inputs and sustainability certifications are expensive and bureaucratic.
- ***Operational Challenges in Reverse Logistics:*** Creating an efficient return and repair infrastructure is expensive and complex, impeding the scaling of circular initiatives.

Interviews Insights:

- Cultural attachment to garments in Indian households fosters reuse and gifting, yet this is often not perceived as 'circular' due to status concerns.
- External support from policymakers and awareness campaigns are vital.
- Consumer misconceptions equate circularity solely with recycling; clear communication is needed.
- The highly fragmented supply chain hampers traceability and full transparency.
- Traceability and upcycling are emerging practices.

POLICY AND PRACTICE RECOMMENDATIONS

Stakeholder	Strategies/Actions	Aligned SDGs	Aligned SDGs	Implementation Steps	Key Performance Indicators (KPIs)
Policymakers	- Enforce EPR for textiles - Fund recycling infra (MRFs) - Incentives for circular SMEs - Ban destruction of unsold goods - Formalize informal waste sector	SDG 12.5, 13.2, 11.6, 15.1	Ellen MacArthur (3Rs), UNEP Sustainable Textiles Roadmap, France Anti-Waste Law	- Enact EPR law with targets - Set recycled-content mandates - Public procurement with recycled fiber - National level campaigns on reuse - Invest in CETPs/ZLD plants	- % textile waste diverted from landfills - % producers complying with EPR - Number of take-back programs funded - Volume of recycled textile waste processed - % increase in formal recycling jobs
Industry (Producers/ Supply Chain)	- Design for disassembly & recyclability (Mono-material designs) - Zero-waste pattern cutting - Use recycled inputs - Internal take-back loops - Collaborate with waste workers	SDG 12.2, 12.5, 13.3, 6.3, 15.1	SAC Higg Index BCI, GRS Certifications OECD Circular Economy Toolkit	- Trace input flows (LCA/ MFA) - Digital tagging/passport for fibers - Join cluster-based CETPs - Partner with startups (fiber-to-fiber recycling) - Set % targets for recycled input	- % recycled content used - Waste generated vs recycled (kg/unit) - Scope 1/2/3 emissions per unit - No. of suppliers engaged in circular sourcing - % products recyclable by design
Brands/ Retailers	- Launch take-back/ repair/resale programs - Use recycled materials (GOTS, RCS) - Disclose circularity data - Promote slow fashion narratives	SDG 12.6, 13.2, 11.6, 15.1	Ellen MacArthur 'Make Fashion Circular' UN Fashion Industry Charter, CTI Indicators	- Setup garment return counters - Eco-label all SKUs - Partner for reverse logistics - Integrate QR-coded clothing info - Join alliances like FashionforGood/ ReSTART	- % lines using recycled/ eco-certified materials - Return rate of garments - % garments reused vs discarded - Customer awareness - Scope 3 emissions
Consumers	- Buy fewer, quality garments - Use repair/reuse/ swapping - Follow labels - Return clothes to take-back - Demand brand transparency	SDG 12.8, 13.3, 15.1	EMF "New Textiles Economy" UNEP Sustainable Lifestyles Fashion for Good Tools	- Participate in clothing swaps - Use second-hand platforms - Scan QR codes for end-of-life info - Join community repair/ upcycling drives - Follow influencers promoting circularity	- % participating in return programs - Clothing donation per capita (kg/year) - % consumers using rental/resale services - Average lifespan of garments owned - Awareness % of circular fashion

CONCLUSION

India's textile industry stands at a pivotal moment, where the adoption of circular economy (CE) principles offers a transformative pathway to reconcile growth with sustainability. This research contributes to the growing body of knowledge by examining the practical, social, and policy-related dimensions of circularity in textiles through a mixed-methods approach, integrating stakeholder perspectives, consumer behavior, and expert interviews.

The findings reaffirm that though the average consumer is getting more aware about the concepts like sustainability and circularity, but the awareness is not backed with actionable steps, circularity initiatives like take back programs, repair options and up cycling initiatives are near to none in Indian ecosystem. Brands are hesitant about investing in these initiatives as certifications and ultra-complex fashion supply chains drain the profit margins & increased product cost market the awareness is not backed with

actionable steps, circularity initiatives like take back programs, repair options and up cycling initiatives are near to none in Indian ecosystem. Brands are hesitant about investing in these initiatives as certifications and ultra-complex fashion supply chains drain the profit margins & increased product cost make the products less desirable.India's transition from a linear to a circular textile model demands a comprehensive ecosystem supported by enforceable policy frameworks, infrastructure for recycling and reverse logistics, technological accessibility for smaller enterprises, and consumer awareness campaigns that resonate across socio-economic segments.

India's traditional strengths such as its rich artisanal heritage and decentralized production clusters can serve as foundational assets in building a culturally grounded, inclusive circular textile economy. However, persistent gaps in data transparency, regulatory incentives, and stakeholder coordination must be addressed.

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