Technological interference for reducing the environmental impact of PV waste in the Indian context

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Abstract

Currently many poor nations recycle PV waste inefficiently and with high levels of pollution. If disposal procedures are not carefully managed, certain hazardous components of PV wastes are toxic to the environment and risk human health. Environmental degradation and pollution are harming to social sustainability. The Indian governments have recently devised a number of environmental management initiatives to control and reduce environmental pollution. By handling PV waste properly, technology may now play a significant part in reducing the negative effects on the environment. Some significant technical interferences are technologies for recycling PV panels, waste collection and management, traceability and labeling systems, incentives for technology adoption, and public awareness via technology. The purpose of this paper is to identify the technological interferences that are reducing the adverse effect on environment of PV waste and futher analysis of causal relationships between them by using DEMATEL method.

Keywords: PV waste, Environmental impact, DEMATEL, Technological interference. Waste management

I. INTRODUCTION

Technological interference, or intervention, can play a crucial role in reducing the impact of photovoltaic (PV) waste on the environment in India. India's rapid adoption of solar energy to meet its growing electricity demands has resulted in a significant increase in the installation of photovoltaic (PV) panels across the country [1]. While this transition to solar power is undoubtedly a positive step towards a more sustainable energy future, it brings with it a pressing concern: the management and environmental impact of PV waste. As these solar panels reach the end of their operational lives, they pose challenges related to disposal, recycling, and the potential release of hazardous materials into the environment [2,3]. Addressing the environmental impact of PV waste is a critical aspect of India's commitment to sustainable energy production. To tackle this issue, technological interference or intervention plays a pivotal role. The integration of innovative technologies and approaches throughout the lifecycle of PV panels, from manufacturing to disposal, can significantly reduce the ecological footprint associated with solar power generation [4].

This comprehensive guide explores a range of technological solutions and interventions aimed at mitigating the adverse effects of PV waste on the environment in India. By harnessing the power of technology, India can not only continue its transition towards cleaner energy but also ensure that the end-of-life management of PV panels aligns with the principles of environmental responsibility and sustainability [5]. We will delve into specific technological interventions and strategies that can be employed at various stages of the PV panel lifecycle to minimize their environmental impact. These encompass recycling techniques, materials recovery innovations, monitoring and maintenance systems, regulatory compliance tools, and collaborative platforms, among others. Each of these interventions contributes to a more circular and eco-friendly approach to solar energy generation in India [6,7]. As the global demand for clean and sustainable energy sources continues to rise, photovoltaic (PV) technology, which converts sunlight into electricity, has emerged as a prominent solution. In countries like India, with abundant sunlight and a growing need for electricity, the widespread adoption of PV panels has been a significant stride towards meeting energy requirements while reducing greenhouse gas emissions [8,9].

However, while solar energy systems offer numerous environmental benefits during their operational phase, they also present a largely unaddressed challenge: the impact of PV waste on the environment [10]. As PV panels reach the end of their useful lives, they become a potential source of environmental concern due to their complex composition and limited recycling infrastructure [11]. This pressing issue highlights the importance of understanding and managing the entire life cycle of PV panels, from their production to disposal, with an emphasis on minimizing their environmental footprint [12,13]. This comprehensive guide explores the multifaceted impact of PV waste on the environment in India, shedding light on the challenges and potential solutions. It investigates into the environmental consequences of improper disposal, the hazardous materials contained within PV panels, and the need for responsible end-of-life management [14,15].

Furthermore, theese guide outlines strategies and interventions that can be adopted to mitigate the environmental impact of PV waste. These include advanced recycling techniques, material recovery innovations, regulatory frameworks, public awareness campaigns, and sustainable manufacturing practices [16,17]. By implementing these measures, India can take significant steps towards achieving a more sustainable and environmentally responsible solar energy landscape, ensuring that the benefits of clean energy are not compromised by the consequences of PV waste.

II. RESEARCH METHODOLOGY

A comprehensive study of numerous reports related to PV waste management that have been published on various platforms, i.e., newspapers, websites, government, and private organizations, has been done to collect data on technological intervention for environmental aspects. Expert opinions were taken to implement the DEMATEL method in the analysis of technological intervention.

III. IDENTIFICATION OF TECHNOLOGICAL INTERFERENCES

Technological interventions of reducing environmental impact of PV waste in the Indian context were identified through regress study of literature, experts' opinion and government and stakeholder policies to handle PV waste.

1) PV Panel Recycling Technologies

Develop and deploy advanced recycling technologies that can efficiently recover materials like silicon, silver, and glass from old solar panels. Technologies such as automated disassembly robots and chemical processes can be explored [17]. Encourage PV manufacturers to design modules with recycling in mind. This includes using fewer materials that are easier to separate during recycling and avoiding hazardous materials.

2) Waste Collection and Management Technologies

Develop digital platforms and mobile apps to help track and manage the collection and transportation of PV waste to recycling centers, ensuring it is handled properly. Utilize data analytics and machine learning to optimize the recycling process. Predictive maintenance and sorting algorithms can improve the efficiency of recycling plants. Establish certification standards for PV panels that consider their recyclability and environmental impact. Panels meeting these standards can receive a "green label," encouraging consumers and businesses to choose eco-friendly options [18]. Develop software tools and platforms to help businesses comply with environmental regulations related to PV waste management, including reporting and tracking requirements [19].

3) Traceability and Labeling Systems

Implement tracking systems, such as QR codes or RFID tags, to trace the manufacturing and disposal history of PV panels. This can help in identifying responsible parties for recycling and disposal. Invest in research to find innovative ways to recover and reuse materials from PV waste, including developing techniques for re-purposing recovered materials in new panel production. Use IoT technology to remotely monitor the health and performance of PV panels [20]. This can help detect issues early and extend the lifespan of panels, reducing the need for premature disposal.

4) Incentives for Technology Adoption

Provide incentives, such as tax breaks or subsidies, for businesses and organizations that invest in advanced PV recycling technologies and sustainable manufacturing practices. Allocate funds to support research and development projects aimed at improving PV recycling technologies and sustainable solar panel materials [21].

5) Public Awareness Through Technology

Use digital and social media platforms to raise public awareness about the importance of PV recycling and environmentally responsible disposal methods. Create online platforms or databases where stakeholders, including manufacturers, recyclers, and policymakers, can collaborate and share best practices and information about PV waste management [22]. These technological interventions can help India reduce the environmental impact of PV waste while promoting a circular economy approach to the solar industry. Collaboration between government, industry, and technology innovators will be essential in implementing these solutions effectively.

These technological interventions can collectively contribute to reducing the environmental impact of PV waste in India.

Table 1: Technological interventions for reducing the impact of photovoltaic (PV) waste on the environment in India:

Technological Intervention	Description	References
PV Panel Recycling Technologies	Advanced recycling methods for recovering materials	[1,3,4,5,17,23,24]
Waste Collection and Management Technologies	Digital platforms for tracking PV waste collection	[1,2,3,4,6.8,13,14,15]
Traceability and Labeling Systems	Tracking systems to trace manufacturing and disposal history	[4,5,7,9,10,11,15,18]
Incentives for Technology Adoption	Tax breaks and subsidies for advanced recycling tech	[1,4,5,8,9,10,14,16]
Public Awareness Through Technology	Digital media for raising public awareness on PV recycling	[3,4,5,7,9,10,16,18,20]

IV. RESULTS AND DISCUSSION

DEMATEL (Decision Making Trial and Evaluation) is a decision-making technique based on pairwise comparisons [25,26,27]. The DEMATEL method can be used to identify the model of causal relations between the variables. It shows causal relations and the factors exerted influences. The advantage of this method is that experts are able to be more fluent in expressing their opinions about the effects (direction and severity of effects) between factors.

Following are the steps of the DEMATEL method for the analysis of technological interventions:

Step 1: Generated the direct relation matrix

To identify the model of the relations among the n criteria, an n × n matrix is first generated. The effect of the element in each row is exerted on the element of each column of this matrix. If multiple experts' opinions are used, all experts must complete the matrix. arithmetic means of all of the experts ' opinions is used and then a direct relation matrix X is generated [26,27].

$$X = \begin{bmatrix} 0 & \cdots & x_{n1} \\ \vdots & \ddots & \vdots \\ x_{1n} & \cdots & 0 \end{bmatrix}$$

The following table shows the direct relation matrix, which is the same as pairwise comparison matrix of the experts.

Table 2; Direct relation matrix

	PV Panel Recycling Technologies	Waste Collection and Management Technologies	Traceability and Labeling Systems	Incentives for Technology Adoption\n	Public Awareness Through Technology
PV Panel Recycling Technologies	0	3	4	3	3
Waste Collection and Management Technologies	3	0	4	4	3
Traceability and Labeling Systems	3	4	0	2	2
Incentives for Technology Adoption	2	2	1	0	2
Public Awareness Through Technology	1	3	4	2	0

Step 2: Computed the normalized direct-relation matrix

To normalize, the sum of all rows and columns of the matrix is calculated directly. The largest number of the row and column sums can be represented by k. To normalize, it is necessary that each element of the direct-relation matrix is divided by k [28].

$$k = max\left\{max\sum_{j=1}^{n} x_{ij}, \sum_{i=1}^{n} x_{ij}\right\}$$

$$N = \frac{1}{k} * X$$

Table 3: Normalized direct-relation matrix

	PV Panel Recycling Technologies	Waste Collection and Management Technologies	Traceability and Labeling Systems	Incentives for Technology Adoption	Public Awareness Through Technology
PV Panel Recycling Technologies	0	0.214	0.286	0.214	0.214
Waste Collection and Management Technologies	0.214	0	0.286	0.286	0.214

Traceability and Labeling Systems	0.214	0.286	0	0.143	0.143
Incentives for Technology Adoption	0.143	0.143	0.071	0	0.143
Public Awareness Through Technology	0.071	0.214	0.286	0.143	0

Step 3: Computed the total relation matrix

After calculating the normalized matrix, the fuzzy total-relation matrix can be computed as follows:

$$T = \lim_{k\to+\infty} (N^1 + N^2 + \cdots + N^k)$$

In other words, an n × n identity matrix is first generated, then this identity matrix is subtracted from normalized matrix and the resulting matrix is reversed. The normalized matrix is multiplied by the resulting matrix to obtain the total relation matrix [26,27,29].

$$\mathrm{T} = \mathrm{N} \times (I - N)^{-1}$$

Table 4: The total relation matrix

	PV Panel Recycling Technologies	Waste Collection and Management Technologies	Traceability and Labeling Systems	Incentives for Technology Adoption	Public Awareness Through Technology
PV Panel Recycling Technologies	0.6	0.932	1.018	0.871	0.813
Waste Collection and Management Technologies	0.805	0.789	1.05	0.954	0.842
Traceability and Labeling Systems	0.721	0.905	0.719	0.759	0.702
Incentives for Technology Adoption	0.475	0.566	0.542	0.413	0.502
Public Awareness Through Technology	0.561	0.789	0.866	0.685	0.511

Step 4: Set the threshold value

The threshold value must be obtained in order to calculate the internal relations matrix. Accordingly, partial relations are neglected and the network relationship map (NRM) is plotted. Only relations whose values in matrix T is greater than the threshold value are depicted in the NRM [28.29,30]. To compute the threshold value for relations, it is sufficient to calculate the average values of the matrix T. After the threshold intensity is determined, all values in matrix T which are smaller than the threshold value are set to zero, that is, the causal relation mentioned above is not considered.

In this study, the threshold value is equal to 0.736. All the values in matrix T which are smaller than 0.736 are set to zero, that is, the causal relation mentioned above is not considered. The model of significant relations is presented in the following table.

Table 5: The total relationships matrix by considering the threshold value

	PV Panel Recycling Technologies	Waste Collection and Management Technologies	Traceability and Labeling Systems	Incentives for Technology Adoption	Public Awareness Through Technology
PV Panel Recycling Technologies	0	0.932	1.018	0.871	0.813
Waste Collection and Management Technologies	0.805	0.789	1.05	0.954	0.842
Traceability and Labeling Systems	0	0.905	0	0.759	0
Incentives for Technology Adoption	0	0	0	0	0
Public Awareness Through Technology	0	0.789	0.866	0	0

Step 5: Final output and created a causal diagram

The next step is to find out the sum of each row and each column of T (in step 3). The sum of rows (D) and columns (R) can be calculated as follows [29,30]:

$$D = \sum_{j=1}^{n} T_{ij}$$

$$R = \sum_{i=1}^{n} T_{ij}$$

Then, the values of D+R and D-R can be calculated by D and R, where D+R represent the degree of importance of factor i in the entire system and D-R represent net effects that factor *i* contributes to the system.

The table below shows the final output.

Table 6: The total relationships matrix by considering the threshold value

	R	D	D+R	D-R
PV Panel Recycling Technologies	3.162	4.234	7.396	1.072
Waste Collection and Management Technologies	3.981	4.44	8.421	0.458
Traceability and Labeling Systems	4.195	3.806	8.001	-0.389
Incentives for Technology Adoption	3.682	2.498	6.18	-1.183
Public Awareness Through Technology	3.37	3.412	6.783	0.042

The following figure shows the model of significant relations. This model can be represented as a diagram in which the values of (D+R) are placed on the horizontal axis and the values of (D-R) on the vertical axis. The position and interaction of each factor with a point in the coordinates (D + R, D-R) are determined by coordinate system.

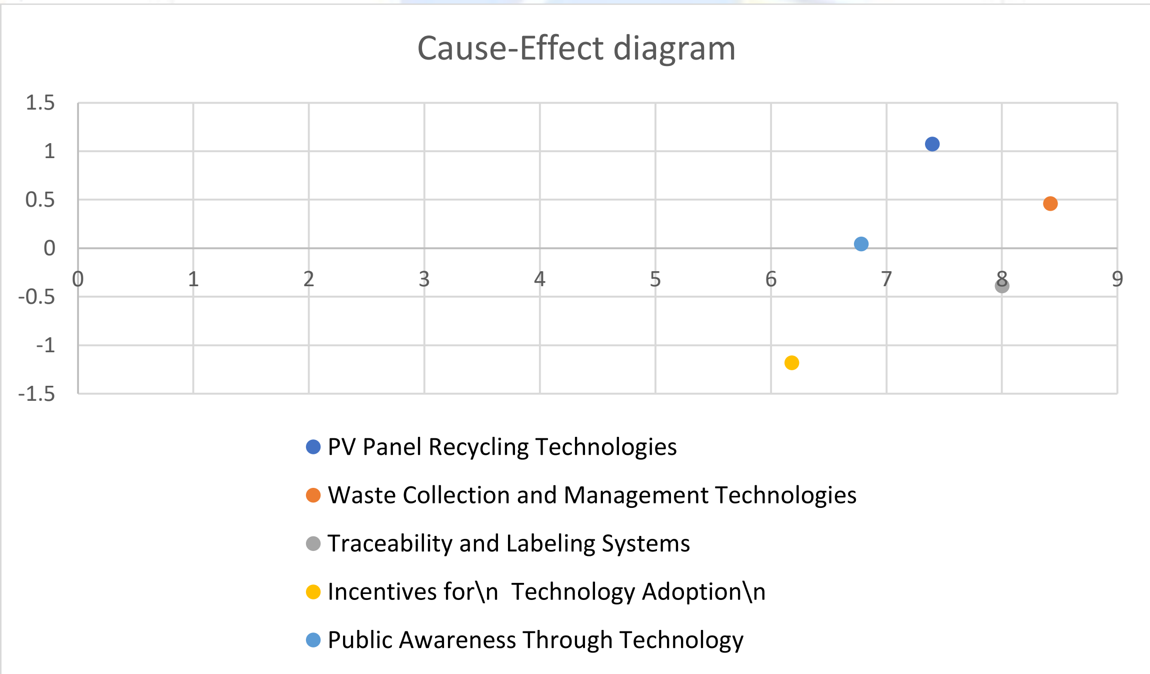

Fig.1 Cause-effect diagram

Step 6: Interpretations of the result

According to the diagram and table above, each factor can be assessed based on the following aspects:

Horizontal vector (D + R) represents the degree of importance between each factor plays in the entire system. In other words, (D + R) indicates both factor i's impact on the whole system and other system factors impacts on the factor. in terms of degree of importance, Waste Collection and Management Technologies is ranked in first place and Traceability and Labeling Systems, PV Panel Recycling Technologies, Public Awareness Through Technology and Incentives for Technology Adoption, are ranked in the next places.

The vertical vector (D-R) represents the degree of a factor's influence on system. In general, the positive value of D-R represents a causal variable, and the negative value of D-R represents an effect. In this study, PV panel recycling technologies,Waste collection and management technologies, Public awareness through technology are considered to be as a causal variable, Traceability and Labeling Systems, Incentives for Technology Adoption are regarded as an effect.

V. CONCLUSIONS

From the above analysis following conclusions were found:

i. Technological intervention analysis has created an eco-friendly reverse supply chain path for handling PV waste.

ii. Adaptation of the latest advanced technology will enhance economy and reduce environmental adverse effect.

iii. PV panel recycling technologies, waste collection and management technologies, public awareness through technology are category of cause while, traceability & labeling systems and incentives for technology adoption are regarded as an effect.

iv. The interference "Waste Collection and Management" was found on top priorities in the analysis.

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