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Fuzzy DEMATEL Analysis of Major Obstacles in Green Recycling of PV waste

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Abstract

In this analysis Fuzzy DEMATEL method was employed to analyze major obstacles in the green recycling of PV waste. This method enables the examination and identification of the intricate causal relationships between the various barriers to efficient recycling. Key obstacles identified include Lack of Standardized Recycling Processes, Technological Challenges, Economic Viability, End-of-Life Collection and Logistics and Environmental Impact. To create a direct-relation matrix, expert opinions were compiled and converted into fuzzy numbers. The matrix was then defuzzied and normalized. The end result is a total-relation matrix that clearly illustrates the interdependencies between each obstacle by emphasizing its prominence and net cause. The results provide insightful information for industry stakeholders and governments that want to improve the sustainability and efficiency of PV waste recycling processes**.**

Keywords: PV Waste; Recycling; Fuzzy DEMATEL; Obstacles

1. Introduction

The challenges associated with environmentally conscious recycling of photovoltaic (PV) waste pose significant impediments to sustainable practices. Addressing the "green recycling obstacles of PV waste" entails grappling with multifaceted issues tied to the disposal and recycling of solar panels. These hurdles range from technological constraints in dismantling PV modules to the lack of standardized recycling procedures. Achieving efficient green recycling demands overcoming the complexity of separating various materials present in solar panels, including glass, metals, and semiconductor materials, to ensure maximum resource recovery. Moreover, challenges extend to the safe handling and disposal of hazardous substances, such as cadmium and lead, commonly found in solar modules. Economic considerations add another layer to these obstacles, as establishing cost-effective recycling methods becomes essential for widespread adoption. Regulatory frameworks must evolve to encourage and enforce environmentally friendly practices, fostering a circular economy for

PV waste. Collaboration among stakeholders, including manufacturers, recyclers, and policymakers, becomes pivotal in developing holistic solutions.

The eco-friendly recycling of photovoltaic (PV) waste presents significant hurdles to sustainable practices.These challenges encompass technological limitations in disassembling PV modules and the absence of uniform recycling protocols(Gerold & Antrekowitsch, 2024) . Effective green recycling necessitates overcoming the intricacies of separating various components in solar panels, such as glass, metals, and semiconductor materials, to maximize resource recovery (Hsu & Kuo, 2020). Furthermore, difficulties arise in the safe management and disposal of harmful substances like cadmium and lead, which are typically found in solar modules (Okorieimoh et al., 2020). Economic factors further complicate these obstacles, as developing cost-effective recycling methods is crucial for widespread adoption (Hassan & Dhimish, 2023). Regulatory frameworks must adapt to promote and enforce environmentally responsible practices and nurture a circular economy for PV waste. Cooperation among various stakeholders, including manufacturers, recyclers, and policymakers, is essential for developing comprehensive solutions.

To confront these multifaceted challenges, researchers are concentrating on creating cutting-edge recycling technologies and processes that can efficiently separate and recover valuable materials from solar panels (Tsanakas et al., 2019). These advanced techniques aim to optimize the extraction of high-value components such as silver, silicon, and rare earth elements, while minimizing waste and environmental impact. For example, some scientists are investigating thermal and chemical methods to break down the complex layered structure of solar panels, enabling more precise material recovery. Moreover, improvements in solar panel design are being explored to facilitate easier disassembly and recycling at the end of their lifespan (Mehmood et al., 2021). This approach, known as "design for recycling," involves reimagining the materials and construction techniques used in solar panels to make them more amenable to future recycling processes. For instance, some manufacturers are exploring the use of alternative adhesives that can be easily dissolved, allowing for simpler separation of glass, silicon, and metal components (Wang et al., 2022) .

The implementation of these strategies would not only address the environmental concerns associated with solar panel waste but also contribute to the circular economy by recovering valuable materials for reuse in new panels or other industries (Tsanakas et al., 2019) . Furthermore, as the global demand for renewable energy continues to grow, efficient recycling processes could help alleviate potential supply chain constraints for critical materials used in solar panel production. By addressing these challenges head-on, the solar energy sector can further enhance its sustainability credentials and continue to play a crucial role in the transition to clean energy sources.

A significant knowledge gap exists within the realm of photovoltaic (PV) waste recycling. This gap encompasses the necessity for more effective and economical recycling techniques as well as the establishment of standardized recycling protocols. This void in understanding offers a chance for cross-disciplinary research partnerships among material scientists, engineers, and environmental specialists. The creation of cutting-edge recycling technologies could enhance resource recovery and minimize the ecological footprint of PV waste. Furthermore, the development of uniform recycling procedures will enable the implementation of consistent and effective recycling practices across various regions and PV technologies.

The purpose of this research is clearly defined, to explore the hurdles and prospects for environmentally friendly recycling of PV waste and to recommend sustainable approaches.

2. Methodology

To assess the current scenery and primary challenges in the green recycling of PV waste, an extensive examination of existing research has been performed. This study employed the Fuzzy DEMATEL technique to evaluate the interconnections among various barriers to effective PV waste recycling. Utilizing insights from experts and information on PV waste recycling techniques, researchers have constructed a direct-relation matrix for analysis. The analysis revealed complex relationships between the different barriers, highlighting the multifaceted nature of green recycling challenges in the PV industry. The findings of this study can serve as a valuable resource for policymakers and industry stakeholders to develop targeted strategies to overcome these obstacles. Furthermore, this research underscores the importance of a holistic approach to addressing PV waste management, considering both technical and non-technical factors that influence recycling efficacy

3. Extraction of Obstacles

This table identifies key challenges in the recycling of PV waste, such as the need for standardized processes, technological difficulties, economic considerations, issues with collection and logistics, and environmental concerns. Addressing these obstacles is crucial for developing sustainable and effective solutions for recycling PV waste. These challenges highlight the multifaceted nature of PV waste recycling, which requires coordinated efforts across various sectors. The development of standardized processes and overcoming technological hurdles could lead to more efficient and cost-effective recycling methods. Implementing effective collection systems and addressing logistical issues are essential to ensure that end-of-life PV modules are properly managed and recycled.

Table 1: Identified barriers

Obstacle	**Description**	**Reference**
Lack of Standardized Recycling Processes	Absence of universally accepted methods for PV module recycling	(Sharma et al., 2023) (Pankadan et al., 2020) (Bajagain et al., 2020) (Lin et al., 2011) (Katenin & Samoilenko, 2022) (Kokul & Bhowmik, 2021) (Oteng et al., 2021) (Lunardi et al., 2018) (Yadav et al., 2023)
Technological Challenges	Difficulty in efficiently separating and recovering materials.	(Lalith Pankaj Raj Nadimuthu et al., 2019) (Gautam et al., 2020) (Yadav et al., 2023) (George & Cekuls, 2024) (Katenin & Samoilenko, 2022) (Rathore & Panwar, 2021) (Oteng et al., 2021) (Chowdhury et al., 2019)

Economic Viability	Limited financial incentives and high recycling costs.	(Pankadan et al., 2020) (Miah et al., 2023) (Sheoran et al., 2020) (Yadav et al., 2023) (Rathore & Panwar, 2021) (Katenin & Samoilenko, 2022) (Bajagain et al., 2020)
End-of-Life Collection and Logistics	Inadequate infrastructure for collecting and transporting PV waste.	(Gautam et al., 2022) (Gautam et al., 2020) (Chowdhury et al., 2019) (Yadav et al., 2023) (Shrestha & Zaman, 2024) (Molano et al., 2022) (Sharma et al., 2023) (Rathore & Panwar, 2021)
Environmental Impact	Concerns about the environmental impact of certain recycling methods.	(Pankadan et al., 2020) (Sheoran et al., 2020) (Jain et al., 2021) (Yadav et al., 2023) (Sharma et al., 2023) (Sheoran et al., 2021)

4. Fuzzy DEMATEL Analysis

Step 4.1: Generated the fuzzy direct- relation matrix

To establish the model of relationships between the n criteria, an initial n × n matrix was created. Within this matrix, the impact of each element in a given row on every element in the corresponding column can be expressed as a fuzzy number. When multiple expert opinions are considered, all experts are required to complete the matrix. Subsequently, the arithmetic average of all expert opinions was used to create the direct relation matrix, z

$$z = \begin{bmatrix} 0 & \cdots & \tilde{z}_{n1} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{1n} & \cdots & 0 \end{bmatrix}$$

The table 2 below indicates the direct relation matrix, which is the same as pairwise comparison matrix of the experts

Table 2: The direct relation matrix

	C1	C2	C3	C4	C5
C1	(0.000,0.000,0.000)	(0.500,0.750,1.000)	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.500,0.750,1.000)

C 2	(0.500,0.750,1.000)	(0.000,0.000,0.000)	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.500,0.750,1.000)
C 3	(0.750,1.000,1.000)	(0.000,0.250,0.500)	(0.000,0.000,0.000)	(0.500,0.750,1.000)	(0.750,1.000,1.000)
C 4	(0.000,0.000,0.250)	(0.500,0.750,1.000)	(0.250,0.500,0.750)	(0.000,0.000,0.000)	(0.750,1.000,1.000)
C 5	(0.250,0.500,0.750)	(0.750,1.000,1.000)	(0.500,0.750,1.000)	(0.500,0.750,1.000)	(0.000,0.000,0.000)

The following table 3 shows the fuzzy scale used in the model.

Table3: Fuzzy Scale

ode	Linguistic terms	L	M	U
1	No influence	0	0	0.25
2	Very low influence	0	0.25	0.5
3	Low influence	0.25	0.5	0.75
4	High influence	0.5	0.75	1
5	Very high influence	0.75	1	1

Step 4.2: Normalized the fuzzy direct-relation matrix

The normalized fuzzy direct-relation matrix can be obtained using the following formula:

$\tilde{x}_{ij} = \frac{\tilde{z}_{\text{ij}}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right)$

where

$$r = \max_{i,j}\left\{\max_{i}\sum_{j=1}^{n} u_{ij}, \max_{j}\sum_{i=1}^{n} u_{ij}\right\} \qquad i,j \in \{1,2,3,\ldots,n\}$$

Table 4: The normalized fuzzy direct-relation matrix

	C1	C2	C3	C4	C5
C 1	0.000,0.000,0.0) (00	0.125,0.188,0.2) (50	0.000,0.063,0.1) (25	0.000,0.000,0.0) (63	0.125,0.188,0.2) (50

C 2	0.125,0.188,0.2)(50	0.000,0.000,0.0)(00	0.000,0.063,0.1)(25	0.000,0.000,0.0)(63	0.125,0.188,0.2)(50
C 3	0.188,0.250,0.2)(50	0.000,0.063,0.1)(25	0.000,0.000,0.0)(00	0.125,0.188,0.2)(50	0.188,0.250,0.2)(50
C 4	0.000,0.000,0.0)(63	0.125,0.188,0.2)(50	0.063,0.125,0.1)(88	0.000,0.000,0.0)(00	0.188,0.250,0.2)(50
C 5	0.063,0.125,0.1)(88	0.188,0.250,0.2)(50	0.125,0.188,0.2)(50	0.125,0.188,0.2)(50	0.000,0.000,0.0)(00

Step 4.3: Calculated the fuzzy total-relation matrix

In step 4.3, the fuzzy total-relation matrix can be calculated by the following formula:

$$\tilde{T} = \lim_{k \to +\infty} (\tilde{x}^1 \oplus \tilde{x}^2 \oplus \dots \oplus \tilde{x}^k)$$

If each element of the fuzzy total-relation matrix is expressed as $\tilde{t}_{ij} = (l^{"}_{ij}, m^{"}_{ij}, u^{"}_{ij})$, it can be calculated as follows:

$$[l^{"}_{ij}] = x_l \times (I - x_l)^{-1}$$
$$[m^{"}_{ij}] = x_m \times (I - x_m)^{-1}$$
$$[u^{"}_{ij}] = x_u \times (I - x_u)^{-1}$$

The process involves first calculating the inverse of the normalized matrix, subtracting it from the identity matrix (I), and finally multiplying the result by the normalized matrix. The fuzzy direct-relation matrix is shown in the subsequent table

Table 5: The fuzzy total-relation matrix

	C1	C2	C3	C4	C5
C 1	(0.034,0.147,0.552)	(0.162,0.329,0.813)	(0.021,0.169,0.612)	(0.022,0.096,0.519)	(0.158,0.343,0.874)
C 2	(0.145,0.305,0.752)	(0.050,0.171,0.613)	(0.021,0.169,0.612)	(0.022,0.096,0.519)	(0.158,0.343,0.874)
C 3	(0.225,0.426,0.863)	(0.099,0.344,0.868)	(0.044,0.186,0.618)	(0.164,0.320,0.770)	(0.267,0.521,1.030)
C 4	(0.056,0.194,0.662)	(0.183,0.380,0.864)	(0.096,0.264,0.707)	(0.042,0.135,0.506)	(0.243,0.457,0.935)

C5	(0.127,0.336,0.860)	(0.242,0.470,0.989)	(0.148,0.335,0.849)	(0.156,0.309,0.796)	(0.103,0.312,0.873)

Step 4.4: Defuzzied into crisp values

The CFCS method has been used to obtain a crisp value of total-relation matrix (Opricovic & Tzeng, 2003) (Zhou et al., 2018) (Yue & Jia, 2013). The steps of CFCS method are as follows:

$$l_{ij}^{n} = \frac{\left(l_{ij}^{t} - \min l_{ij}^{t}\right)}{\Delta_{min}^{max}}$$

$$m_{ij}^{n} = \frac{(m_{ij}^{t} - min\ l_{ij}^{t})}{\Delta_{min}^{max}}$$

$$u_{ij}^{n} = \frac{(u_{ij}^{t} - min\ l_{ij}^{t})}{\Delta_{min}^{max}}$$

So that

$$\Delta_{min}^{max} = \max u_{ij}^{t} - \min l_{ij}^{t}$$

Calculating the upper and lower bounds of normalized values:

$$l_{ij}^{s} = m_{ij}^{n} / (1 + m_{ij}^{n} - l_{ij}^{n})$$

$$u_{ij}^{s} = u_{ij}^{n} / (1 + u_{ij}^{n} - l_{ij}^{n})$$

The output of the CFCS algorithm is crisp values.

Calculating total normalized crisp values:

$$x_{ij} = \frac{[l_{ij}^{s}(1 - l_{ij}^{s}) + u_{ij}^{s} \times u_{ij}^{s}]}{[1 - l_{ij}^{s} + u_{ij}^{s}]}$$

Table 6: The crisp total-relation matrix

	C1	C2	C3	C4	C5
C1	0.214	0.398	0.238	0.169	0.42
C2	0.365	0.244	0.238	0.169	0.42
C3	0.466	0.408	0.253	0.377	0.566
C4	0.268	0.441	0.325	0.197	0.512

C5	0.398	0.522	0.397	0.372	0.304

Step 4. 5: Set the threshold value

This allows for the creation of the network relationship map (NRM) by disregarding partial relations. NRM only displays connections whose values in matrix T exceed the threshold. Calculating the average values of the matrix T is sufficient to establish this threshold. Once the threshold intensity is set, any values in matrix T that fall below it are zeroed out, effectively eliminating the causal relationships from consideration. In this study, the threshold value is equal to 0.3510.351

In matrix T, any value below 0.351 is zeroed out, effectively disregarding the aforementioned causal relationship. The subsequent table displays the model of significant relationship.

Table 7: The crisp total- relationships matrix by considering the threshold value

	C1	C2	C3	C4	C5
C1	0	0.398	0	0	0.42
C2	0.365	0	0	0	0.42
C3	0.466	0.408	0	0.377	0.566
C4	0	0.441	0	0	0.512
C5	0.398	0.522	0.397	0.372	0

Step 4.6: Final output and create a causal relation diagram

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

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

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

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.

Table 8: The final output

	R	D	D+R	D-R

C1	1.711	1.438	3.15	-0.273
C2	2.013	1.436	3.449	-0.576
C3	1.451	2.07	3.521	0.619
C4	1.284	1.742	3.026	0.459
C5	2.311	2.083	4.393	-0.228

The model of significant relationships is shown in the subsequent figure 1. This model can be visualized as a coordinate system where the horizontal axis represents (D+R) values and the vertical axis represents (D-R) values. Each factor's position and interaction within this system is determined by it.

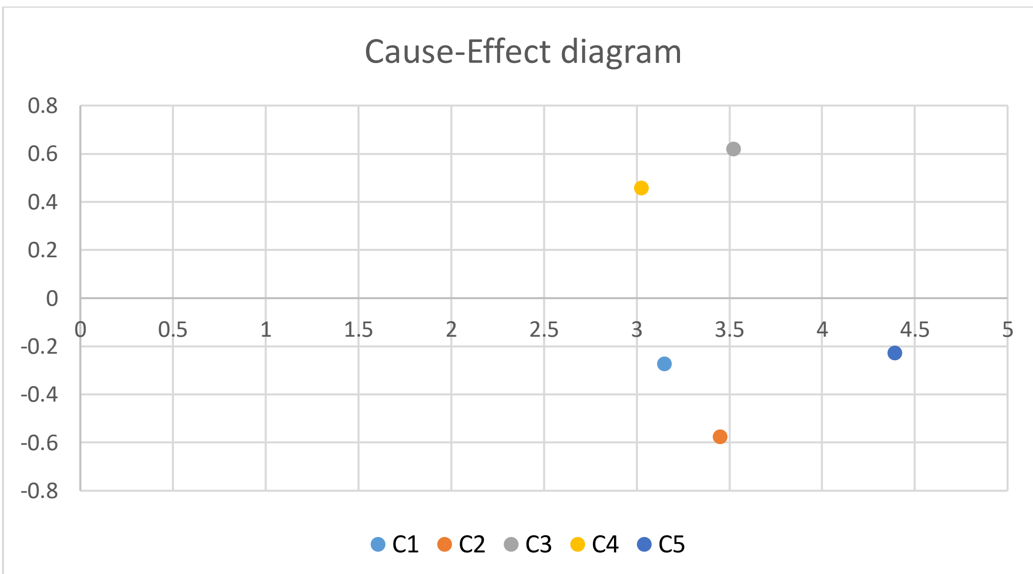

Figure 1: cause-effect diagram

5. Results and Discussion

The illustration and data set offer a comprehensive view of how various factors can be assessed based on two crucial dimensions.

The D+R vector, represented horizontally, signifies the overall importance of a factor within the system. This encompasses both the effect of factor i on the entire system and the impact of other system elements on factor i. In terms of significance, C5 was ranked highest, followed by C3, C2, C1, and C4 in descending order. This research categorizes C3 and C4 as causal elements, while C1, C2, and C5 are classified as effects.

The D-R vector, depicted vertically, indicates the degree to which a factor impacts the system. Typically, a positive D-R value suggests a causal element, while a negative D-R value implies an effect. Regarding importance, C5 tops the list, succeeded by C3, C2, C1, and C4. In this study, C3 and C4 were identified as causal elements, whereas C1, C2, and C5 were labelled as effects.

This classification of variables into causal or effect groups provides valuable insights into the system's operations and interconnections. The absolute value of D-R serves as a measure of a factor's influence, with larger values indicating more significant impacts on the system. This ranking of factors based on their relative importance can guide decision-makers in prioritizing interventions and optimizing resource distribution for effective system management.

The study highlights the significance of the factors within the system, with C5 being the most influential factor followed by C3 and C2. The identification of causal and effect variables provides valuable insights for future research and decision-making in the field of PV waste management.

The Fuzzy DEMATEL method was employed in this study to analyse key obstacles in the eco-friendly recycling of photovoltaic (PV) waste, providing crucial insights into the complex interrelationships among various barriers. The research identified five main challenges: Lack of Standardized Recycling Procedures, Technical Limitations, Economic Viability, End-of-Life Retrieval and Transportation, and Environmental Consequences.

6. Conclusion

Results revealed that Environmental Consequences (C5) was the most crucial factor, succeeded by Economic Viability (C3) and Technical Limitations (C2). The analysis categorized Economic Viability (C3) and End-of-Life Retrieval and Transportation (C4) as cause variables, while Lack of Standardized Recycling Procedures (C1), Technical Limitations (C2), and Environmental Consequences (C5) were classified as effects.

These outcomes emphasize the interconnected nature of the challenges in PV waste recycling and stress the need for a holistic approach to tackle them. The identification of cause-and-effect variables offers valuable guidance for prioritizing efforts and resources in developing sustainable PV waste management solutions. This research underscores the importance of addressing environmental issues, improving economic feasibility, and overcoming technical hurdles to enhance the efficiency and sustainability of PV waste recycling processes. Future studies should delve deeper into the relationships between these factors and explore potential applications of these findings in various Physical Science subfields.

In summary, this investigation contributes to the understanding of the intricate challenges in PV waste recycling and lays the groundwork for developing targeted strategies to overcome these obstacles. The insights gained from this study can guide policymakers, industry stakeholders, and researchers in their efforts to improve the sustainability of the solar energy sector and promote a circular economy for PV waste management.

7. Future Scope:

The future scope of this research lies in further exploring the relationships between the factors and their impact on the system. Additionally, investigating the potential applications of the findings in various subfields of Physical Science could provide valuable contributions to the field

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