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A plithogenic based neutrosophic analytic hierarchy process framework to analyse the barriers hindering adoption of eco-innovation practices in supply chain

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ABSTRACT

Eco-innovations have become an essential component to attain sustainability in the supply chain. However, the process of transition from the traditional supply chain to an eco-innovative focused supply chain is faced with several challenges especially in the developing nations. Hence, this study is undertaken to evaluate the eco-innovation implementation barriers in the supply chain. A plithogenic-based neutrosophic analytic hierarchy process is used to determine the weight intensity of the barriers. Findings of the study indicate that lack of internal funds necessary to meet the extra cost and research and development cost are the major barrier in the adoption of eco-innovation initiatives. The other important barriers hindering the adoption of eco-innovation initiatives include the absence of complementary assets (such as infrastructure, standards), lack of collaboration agreements with other organisations, and high costs involved in the transition to new technologies. A manufacturing case industry is selected to apply the proposed framework. This study will help the industry experts/policy-makers to understand the important barriers hindering the adoption of eco-innovation initiatives.

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Eco-innovation; supply chain; barrier; plithogenic; neutrosophic analytic hierarchy process

1. Introduction

The way manufacturing industries supply chain (SC) are exploiting the natural resources, polluting the environment through their operations, and managing the waste, is no more hidden and has become a major concern for the entire world. These issues are more prevalent in developing countries rather than in developed countries. This is because the main focus of the developing countries is to develop their economy and while doing so the sustainability of the SC is usually compromised (Wang et al. 2019). Manufacturing operations are core to the economic growth of developing countries. While at one end increased manufacturing activities have improved the living standards and prosperity of the society but on the other hand, the environmental and social problems have risen. The rising environmental crisis, social inequalities, and pollution have forced developing countries to create a balance between economic development and environmental degradation. In this context, the manufacturing organisations are under severe pressure that they minimise their environmental impacts and maximise their social and economic factors (Mavi, Saen, and Goh 2019). To address this, it has become necessary that decision-makers (DMs) integrate sustainable dimensions (social, economic, and environmental) coupled with innovations in the production system and social behaviour patterns in the SC. Eco-innovation is an innovation that minimises the environmental impacts of manufacturing and consumption activities even if it was initially intended or not (OECD 2009).

Eco-innovation is defined as 'the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives' (Kemp and Pearson 2008). It can reduce the environmental impact of the SC along with value addition (Bitencourt et al. 2020). Adoption of eco-innovation practices can help organisations develop novel products that use clean energy, create less pollution, and can be recycled (Severo, De Guimarães, and Dorion 2018). Moreover, eco-innovation results in economic benefits such as reduced product and service cost through efficient resource utilisation and better logistics management (Lee, Wu, and Tseng 2018). Furthermore, the increase in prosperity of the society coupled with sustainability, creation of competitive economy, new industries being set-up, and employment generation are the social benefits of eco-innovation practices adoption (Carrillo, del Río González, and Könnölä 2009). Eco-innovation also helps create brand image in the market and better relationships with the consumers, suppliers, employees, and authorities (Sarkar 2013).

Eco-innovation-related studies have been mainly concentrated in developed nations especially the European nations and the USA (Díaz-García, González-Moreno, and Sáez-Martínez 2015). At the same time, developing countries are still striving hard to adopt eco-innovation fully (Aloise and

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Macke 2017); although its adoption results in several socio-economic-environmental advantages. Several barriers exist that hamper the implementation of eco-innovation initiatives in the context of developing countries (Aloise and Macke 2017). Hence, it has become imperative to identify and understand the barriers that hinder organisations from the adoption and implementation of eco-innovation initiatives. Numerous research contributions can be found in the literature that have investigated eco-innovation implementation barriers. Of these studies, researchers from developed countries especially European nations such as the UK, Netherland, Germany, and Spain contribute to a great extent with very little research from the developing countries. The rare contribution reported on eco-innovation barriers from developing countries are Brazil, India, and Nigeria. Further, the analysis reveals that these studies have limited focus: Aloise and Macke (2017) identify the eco-innovation barriers but does not determine their severity using multi-criteria decision making (MCDM) technique; Orji et al. (2019) determine the intensity of eco-innovation barriers but their study is limited to freight logistics industry. In the Indian context, Karuppiah et al. (2020) evaluate the green manufacturing barriers using the MCDM technique but restrict their work to small- and medium-sized enterprises (SMEs); and Ravi (2015) models the relationship between eco-innovation challenges but does not rank them according to their importance weight. Limited research could be found regarding the evaluation of eco-innovation barriers in the context of large scale Indian manufacturing industries. This research work mainly focuses on the Indian large-scale manufacturing industries.

The contribution of large-scale manufacturing industries is approximately 20–25% of the total India's GDP (Sarkis, Zhu, and Lai 2011). According to the World Bank Report, in the year 2016 India's manufacturing sector alone contributed about 16% of GDP, which is higher than the 2015 global average (15%). Further, looking at India's optimistic approach to become a global manufacturing hub and shaping itself as an attractive investment destination, it is expected that the manufacturing sector will generate about 100 million additional jobs by the year 2025. However, the growth of manufacturing sectors especially the large-scale manufacturing industries is linked with the creation of several environmental problems such as air pollution, water pollution, effluent run-off, and improper disposal of waste (Ganapathy et al. 2014). In developing countries, environmental degradation due to manufacturing activities and social disparity has been a point of discussion in recent years. It has thus become imperative that manufacturing organisations immediately start taking measures to adopt eco-innovative initiatives for sustainability. But, to enhance the adoption rate of eco-innovation initiatives it is necessary to eliminate the barriers associated with it. However, the eco-innovation barriers cannot be mitigated unless they are clearly understood and further analysed to determine the most important barrier over the others. The determination of the intensity weight of each barrier will help the decision-makers/policy-makers feel more confident in addressing the barriers through the development of appropriate strategies. In this regard, the authors lay down the objectives of this study.

The objectives of the present research work is as follows:

- To identify the barriers that hamper eco-innovation initiatives in Indian large-scale manufacturing industries.
- To rank the eco-innovation barriers from the most important one to the least important one.

To accomplish the above-proposed objectives, firstly the key eco-innovation barriers were identified based on the literature analysis of relevant articles and inputs received from the DMs panel. This led to the identification of a total of 28 barriers categorised under five main barriers. Secondly, a plithogenic-based neutrosophic analytic hierarchy process (AHP) approach is applied to determine the weight intensity of the identified eco-innovation barriers. AHP is the most used subjective weighing method in the literature to determine the criteria weight intensity (Ansari and Kant 2017; Khan et al. 2020). However, AHP in its simplest form fails to address the imprecision inherent in human judgements.

The limitation associated with the traditional AHP technique is addressed in this research work by integrating neutrosophic set which was introduced by Samarandache in the year 1995. Neutrosophic set is an extension to classical, fuzzy and intuitionistic fuzzy set (IFS) (Smarandache 2003). A neutrosophic set is characterised by truth, indeterminacy, and falsity degrees to represent the uncertain and inconsistent human information (Smarandache 1998, 1999). The truth, indeterminacy, and falsity degrees of neutrosophic theory are independent of each other. The neutrosophic set has the ability to deal with incomplete, indeterminate, and inconsistent information but, the classical fuzzy set and IFS are capable of dealing with only partial or incomplete information (Abdel-Basset, Manogaran, and Mohamed 2019). This study uses neutrosophic AHP to rank the barriers hindering eco-innovation adoption. Further, this study attempts to increase the accuracy of aggregation by applying the plithogenic set aggregation operator which considers equidistant contradiction degree value between each criteria and the most important criteria (dominant one). Plithogenic set was introduced in 2017 by Smarandache which is a generalisation of crisp, fuzzy, intuitionistic fuzzy, and neutrosophic sets and is obtained from plithogeny. To apply the proposed plithogenic based neutrosophic AHP framework a manufacturing case industry is selected.

The main contributions of this study are as follows:

- This study expand the present knowledge of body on eco-innovation by exploring 28 barriers hampering its adoption in large-scale manufacturing sectors in the context of developing nations
- The present research work validates the proposed framework by applying it to a case manufacturing industry
- This study apply a plithogenic-based neutrosophic AHP framework to determine the weight intensity of eco-innovation barriers
- The present study rank the barriers in a sequence according to their importance of weight (i.e. weight intensity) obtained

- This study propose theoretical and practical implications for the decision-makers/policy makers to enable them formulate appropriate strategies

The remaining part of the article is sequenced as follows: Section 2 briefly discusses the literature review. The proposed methodology used in this research work and its application to a case manufacturing industry is presented in Section 3. Section 4 presents the results discussion and sensitivity analysis. Finally, the conclusion of the research work is provided in Section 5.

2. Literature review

The literature review section consists of three subsections. The first subsection presents a brief explanation of the previous research contributions on eco-innovation. The research gaps derived from the past literature analysis is discussed in the second subsection. Finally, the third subsection presents the barriers hindering the adoption of eco-innovation initiatives.

2.1 Previous research contributions

Several research contributions on eco-innovation can be found in the literature in the context of developed countries as well as developing countries. Wilts et al. (2013) studied the barriers inhibiting eco-innovation adoption in the waste prevention domain. The results of the study are based on the analysis of three case studies in the German context. Marin, Marzucchi, and Zoboli (2015) analyse the European SMEs with a special focus on factors inhibiting eco-innovation and eco-innovation engagement. This study conducted a survey interview in multiple sectors and then based on cluster analysis presented their results. Ravi (2015) analyzes ten challenges that hinder the adoption of eco-efficiency practices in the Indian electronics packaging industry. This study applied interpretive structural modelling to evaluate the inter-relationship between the challenges. Polzin, von Flotow, and Klerkx (2016) empirically explore the role of institutional innovation intermediaries to address the eco-innovation barriers especially through mobilisation of financial resources along the innovation process. The authors collected data by conducting in-depth interviews and then analysing it using software MaxQDA 11 the results were presented.

Aloise and Macke (2017) identify the challenges faced by the Brazilian organisations in the adoption of eco-innovations. In this study, the authors present the results by conducting a structured interview with industrial companies of the Manaus Free Trade Zone (MFTZ). Ghisetti et al. (2017) studied the impact of financial barriers on the adoption of environmental innovations in European SMEs. The authors conducted a survey and then applied the bivariate probit model to present their results. Gupta and Barua (2018) develop a framework to mitigate the green innovation barriers. They propose an integrated BWM-fuzzy TOPSIS MCDM approach to rank the solutions to overcome the eco-innovation barriers. Arranz et al. (2019) identify and analyse the hindering factors of eco-innovation for Spanish SMEs. The authors surveyed to collect the input data. They then used an exploratory factors analysis to compute the results. Simms et al. (2020)identified the important barriers hindering the adoption of waste-reducing eco-innovations in the UK and Netherland food industry. The authors based on empirical analysis (interview) proposed a conceptual framework that depicts the interrelatedness of each barrier at different levels of the SC to eco-innovate.

Kiefer, Del Rio Gonzalez, and Carrillo-Hermosilla (2019) examine the role of the firm's internal factors (resources, competencies, and capabilities) as barriers to different types of eco-innovation in Spanish SMEs. To present the results the authors collect data through a survey and then conducted an exploratory factor analysis. Orji et al. (2019) analyse the eco-innovation implementation challenges for sustainability in the Nigerian freight logistics industry. This study prioritised the 18 barriers using Best Worst Method (BWM) to identify the most influential barrier. Karuppiah et al. (2020) identify 25 green manufacturing implementation barriers for SMEs in the Indian context. They further rank the barriers using an integrated decision making trial and evaluation laboratory-analytic network process-technique in order of preference by similarity to ideal solution (DEMATEL-ANP-TOPSIS) approach. Mitchell, O'Dowd, and Dimache (2020) developed an online sustainability and eco-innovation framework for SMEs to overcome the barriers hindering environmental initiatives. Table 1 presents the summary of previous literature in context of subject focused, methodology used, industry considered and country context.

2.2 Research gaps

It is clear from the literature analysis that research contributions related to the analysis of eco-innovation adoption barriers exist. However, a thorough analysis of the published literature in the context of eco-innovation and barrier analysis helps to unearth several research gaps. Some studies cannot be considered extensive as they are limited to either identification of specific types of eco-innovation barriers or focus on a specific subject. For instance, resources, competencies, and capabilities related to eco-innovation barriers (Kiefer, Del Rio Gonzalez, and Carrillo-Hermosilla 2019); financial barriers for eco-innovation (Ghisetti et al. 2017); and eco-innovation barriers for waste reduction (Simms et al. 2020); Wilts et al. 2013). The study conducted by Polzin, von Flotow, and Klerkx (2016) emphasises how eco-innovation barriers can be addressed through financial mobilisation. This study does not evaluate and compute the intensity of each barrier. Most of the eco-innovation barrier-related studies have been conducted in developed economies such as the UK, Netherland, Germany, Spain, or survey conducted in European countries. Limited research can be found in developing economies, especially in the Indian context. It is also found that the findings of most of the research works are based on surveys or structured interviews.

The research contributions (Karuppiah et al. 2020; Orji et al. 2019; Ravi 2015) that have developed a MCDM-based eco-innovation framework and then validated by applying it to a select case organisation is limited. Gupta and Barua (2018) proposed a hybrid BWM-fuzzy TOPSIS to rank the solutions mitigating green innovation barriers. However, the findings of

Table 1. Summary of previous literature.

Reference	Subject	Method	Industry type	Country context
Wilts et al. 2013	Eco-innovation barriers in the waste prevention field	Case-studies	Not-mentioned	Germany
Marin, Marzucchi, and Zoboli (2015)	Factors hindering eco-innovation and its integration	Survey and cluster analysis	SMEs	European
Ravi (2015)	Challenges that hinder eco-efficiency	ISM	Electronics	India
Polzin, von Flotow, and Klerkx (2016)	Role of institutional innovation intermediaries to address the eco-innovation barriers	MaxQDA 11 software	Project-managing organisations	Germany
Aloise and Macke (2017)	Eco-innovation adoption challenges	Content analysis	Multiple industries	Brazil
Ghisetti et al. (2017)	Role of financial barriers on adoption of environmental innovations	Bivariate probit model	SMEs	European nations
Gupta and Barua (2018)	Rank the green innovation barriers solutions	BWM-fuzzy TOPSIS	SMEs	India
Arranz et al. (2019)	Factors hampering eco-innovation initiatives	Exploratory factor analysis	SMEs	Spain
Simms et al. (2020)	Factors impeding waste-reducing eco-innovations	Cross-case analysis	Food industry	UK and Netherlands
Kiefer, Del Rio Gonzalez, and Carrillo-Hermosilla (2019)	Role of firm's internal factors on different eco-innovations	Exploratory factor analysis	SMEs	Spain
Orji et al. (2019)	Eco-innovation adoption challenges	BWM	Freight logistics industry	Nigeria
Karuppiah et al. (2020)	Green manufacturing adoption initiatives	DEMATEL-ANP-TOPSIS	SMEs	India
Mitchell, O'Dowd, and Dimache (2020)	Eco-innovation framework to mitigate the barriers	NVivo software	SMEs	European nations

the study are limited to SMEs. Orji et al. (2019) proposed a BWM-based framework to rank the eco-innovation barriers for the Nigerian freight logistics industry. But the findings of this study cannot be generalised for manufacturing industries. Karuppiah et al. (2020) developed an integrated DEMATEL-ANP-TOPSIS framework to analyse green manufacturing practices adoption barriers. This study is conducted in the Indian context but the findings are based on inputs from SMEs. Ravi (2015) models the linkages between the eco-innovation challenges using ISM for the Indian electronics packaging industry. The ISM technique does not determine the most influential barrier but it only models the inter-relationship between the criteria.

Following are the gaps identified based on the analysis of existing knowledge body of the research topic:

- Evaluation of eco-innovation barriers for large-scale manufacturing organisations in developing economies especially in the Indian context is rare
- A MCDM framework that computes the weight intensity of eco-innovation barriers and ranks them based on their importance for large-scale Indian manufacturing organisations is still missing.
- Application of neutrosophic sets to handle the uncertainty associated with human judgements is limited in the previous research contributions. Further, the use of plithogenic-based aggregation operation to increase the accuracy of aggregation for the inputs of different decision-makers is rare.

In the problems having multiple conflicting criteria it is very difficult for the DMs to decide whether which criteria should be given priority. In such conditions, the computation of severity of each criteria using a suitable MCDM approach would help the DMs arrange the criteria from most important to least important. The quantitative evaluation of criteria using an appropriate MCDM approach helps the DMs feel more confident during decision-making. To fill the above research gaps and for better decision-making, there is an immediate need to determine the weight intensity of eco-innovation barriers and rank them. The justification for the objective of this research work is thus fullfilled.

2.3 Identification of barriers hindering adoption of eco-innovation initiatives

The potential barriers hindering the adoption of eco-innovation initiatives in the SC are identified based on the literature survey and inputs from the DMs panel. The DMs also categorised the finalised 28 barriers along five main dimensions namely, organisational and management barriers, economic and financial barriers, strategic barriers, social and market barriers, and environmental and legal barriers. Table 2 presents the barriers and sub-barriers with description.

3. Research methods

This section explains the plithogenic set, neutrosophic set, the procedure of the proposed plithogenic based neutrosophic AHP approach and the research framework of the considered problem.

3.1 Plithogenic set

Plithogenic set introduced by Smarandache (2017) is the initiation, conception, development, and evolution of new entities from fusions of contradictory and non-contradictory multiple old entities. Plithogenic set (P, A, V, d, c) is a set that consist of several elements termed as multi-dimensional attributes

Table 2. List of eco-innovation barriers with description.

Sr. No.	Eco-innovation barriers with code	Description	Reference
Organizational and Management Barriers (OMB)			
1	Lack of management models to acquire novel information on markets and technologies (OMB1)	Organization fails to gather the information regarding the novel necessities of the market and availability of new environmental technologies due to lack of management system models	Arranz et al. (2019)
2	Lack of in-house technical capacity, skilled technicians/ engineers to operate eco-innovation technologies (OMB2)	Unavailability of in-house expertise and trained technician presents a challenge for effective adoption novel and clean technologies	Luken and Van Rompaey (2008); Orji et al. (2019)
3	Lack of sustainable management strategies in corporate strategy planning (OMB3)	The diffusion of sustainability dimensions in the existing corporate strategy as well as the necessity to undergo changes in organisational structure is challenging for the organisations	Carrillo, del Río González, and Könnölä (2009)
4	Lack of communication network between the manufacturer and consumer (OMB4)	Due to communication gap between the producer and consumer, the manufacturer fails to understand what the consumer needs and hence affects the marketability of eco-innovative products	Carrillo, del Río González, and Könnölä (2009); Orji et al. (2019)
5	Uncertainties of innovation outcomes and time consuming process (OMB5)	Because the innovation process requires more time than what is expected and further the outcomes realised from it are also uncertain and hence organisations show less interest in this process	Tidd and Bessant (2020); Carrillo, del Río González, and Könnölä (2009)
6	Short-term thinking of the management (OMB6)	In developing economies organisations mainly focus on short-term financial gains which hinder the adoption of eco-innovation initiatives as its pay-back periods are longer	Carrillo, del Río González, and Könnölä (2009)
Economic and Financial Barriers (EFB)			

(*Continued*)

Table 2. (Continued).

Sr. No.	Eco-innovation barriers with code	Description	Reference
7	High costs involved in the transition to new technologies (EFB1)	High capital investment to procure advanced and environmentally friendly technologies act as an important barrier for adoption of eco-innovations practices	Carrillo, del Río González, and Könnölä (2009); Gupta and Barua (2018)
8	Lack of internal funds necessary to meet the extra cost and research and development (R&D) cost (EFB2)	Organizations have limited funds to finance the extra costs needed for eco-innovation initiatives implementation in the form of creation of more resources and investment in R&D	Arranz et al. (2019)
9	Lack of financial support from government institutions (EFB3)	Organizations lack the financial assistance from government institutions to develop R&D centres with a highly trained and skilful human capital base at the initial stages of adoption of eco-innovation	Experts opinion
10	Lack of organisational understanding regarding the cost saving potentials of eco-innovation (EFB4)	Organizations negative perception that eco-innovations are costly and failure to understand the cost savings in the form of raw material and energy consumption hinders the adoption of eco-innovation initiatives	Carrillo, del Río González, and Könnölä (2009); Orji et al. (2019)
11	Uncertain returns on eco-innovation investment (EFB5)	The returns on investment made in skill development, cleaner technologies and R&D are uncertain and hence organisation fear to invest in eco-innovations	Marin, Marzucchi, and Zoboli (2015)
12	Lack of incentives to reduce material and energy use (EFB6)	There is lack of policy or regulatory structure from government institutions regarding incentives such subsidies, grants or tax credits on eco-innovation hence organisations are not motivated to adopt eco-innovation initiatives	Marin, Marzucchi, and Zoboli (2015); Polzin, von Flotow, and Klerkx (2016); Gupta and Barua (2018)
Strategic Barriers (SB)			

(*Continued*)

Table 2. (Continued).

Sr. No.	Eco-innovation barriers with code	Description	Reference
13	Lack of collaboration agreements with other organisations (SB1)	Conflicting objectives of two or more organisations restrict them to collaborate with each other and hence fail to exchange experience, technology and knowledge acquired by each other in their eco-innovation activities	Abdel-Baset et al. (2019)
14	Lack of cooperation agreement with suppliers (SB2)	Greening the material, reduction of waste or pollution and innovations in energy savings is difficult to achieve without collaborative engagements with the suppliers	Abdel-Baset et al. (2019)
15	Absence of complementary assets (such as infrastructure, standards) (SB3)	Organisations failure to understand the complexity of eco-innovation and lack of investment in R&D hinders the development of infrastructure and standards which is usually technology driven and cost challenging	Polzin, von Flotow, and Klerkx (2016)
16	Co-ordination problems between innovators (e.g. entrepreneurs), financiers and government (SB4)	Government institutions, innovators and financiers fail to work in close collaboration and foster knowledge flows with each other and thus fail to reduce the uncertainty and information asymmetries	Polzin, von Flotow, and Klerkx (2016)
17	Lack of inter-departmental co-ordination (SB5)	For effective adoption of eco-innovation practices the environmental initiatives need to be assigned to all the departments. Failure of all the departments to coordinate and work towards the common sustainable objectives hampers eco-innovation adoption	Aloise and Macke (2017)
Social and Market Barriers (SMB)			
18	Lack of marketing capabilities (SMB1)	Lack of environmental consciousness among the managerial staff hinders the promotion and marketability of the eco-innovation product as green product to customers and hence fail to increase its demand	Polzin, von Flotow, and Klerkx (2016); Karuppiah et al. (2020)
19	Continuously changing market conditions (SMB2)	High uncertainty in the market especially consumer behaviour towards eco-innovative product affects the diffusion of eco-innovation initiatives. Organisation does not know which type of market conditions are suitable for eco-innovation	Díaz-García, González-Moreno, and Sáez-Martínez (2015)
20	Insufficient pressures from social actors (consumers, policy makers, NGOs, etc.) to eco-innovate (SMB3)	Organisation lacks sufficient pressure from the consumers, policy makers, NGOs, etc., to engage in eco-innovation practices especially in the developing economies	Carrillo, del Río González, and Könnölä (2009); Karuppiah et al. (2020)
21	Poor response of consumer to innovative products (SMB4)	The consumers in developing countries search for good quality cheaper products and hence the costly eco-innovative products fail to attract the consumers	Expert Opinion
22	Cultural resistance to change from the traditional practice (SMB5)	It would be difficult for an organisation to engage in eco-innovation initiatives where employees resist to change from the traditional working system develop nature of adaptation	Carrillo, del Río González, and Könnölä (2009); Orji et al. (2019)
23	Low awareness of consumer/ purchaser about the environmental problems (SMB6)	Lack of knowledge among the consumers/ purchasers regarding the environmental impact created by non-green products deters the implementation of eco-innovation initiatives	Carrillo, del Río González, and Könnölä (2009); Gupta and Barua (2018)
Environmental and Legal Barriers (ELB)			

(Continued)

Table 2. (Continued).

Sr. No.	Eco-innovation barriers with code	Description	Reference
24	Absence of stringent environmental policies (ELB1)	Inexistence of a strong environmental regulations and policies fails to create sufficient pressure on the organisation to adopt eco-innovation initiatives	Tumpa et al. (2019)
25	Environmental problems are given least priority (ELB2)	Organizations do not view environmental problems as one of their key social responsibility. This holds them back in adoption of eco-innovation initiatives	Carrillo, del Río González, and Könnölä (2009)
26	Poor implementation level of EMS (ELB3)	Organisations fail to effectively monitor and control the environmental impacts of their production operations due to improper implementation of EMS	Wagner (2008)
27	Lack of environmental/ sustainability capabilities (ELB4)	Organisations lack the required capabilities to embed the environmental factors or sustainability dimensions in the SC which hinders the adoption of eco-innovation initiatives	Experts opinion
28	Lack of favourable environmental policies on adoption of eco-innovation practices (ELB5)	Highly expensive environmentally cleaner technologies need to be adopted to implement eco-innovation initiatives. Absence of favourable environmental policies that support organisation to procure these technologies deters the adoption of eco-innovation practices	Experts opinion

$A = \{\alpha_1, \alpha_2, \ldots, \alpha_m\}$, $m \geq 1$, wherein each attribute has values $V = \{v_1, v_2, \ldots\ldots, v_n\}$, $n \geq 1$. In plithogenic set, each attribute's value has two important features namely the degree of appurtenance and degree of contradiction. Each attribute's value (V) has corresponding degree of appurtenance $d(x, v)$ of the element x, to the set P, with respect to some given criteria. The contradiction (dissimilarity) degree function $c(v, D)$ presents the relation between each attribute and the dominant (most important attribute) value. To achieve better accuracy for the plithogenic aggregation operators (intersection, union, complement, inclusion, equality) the contradiction degree function is the main feature.

Definition 1: Let the two plithogenic set be $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ (1)

The plithogenic intersection is:

$$\tilde{a} \wedge_p \tilde{b} = ((a_1, a_2, a_3), 1 \leq i \leq n) \wedge_p ((b_1, b_2, b_3), 1 \leq i \leq n) \\ = \left((a_1 \wedge_p b_1), \frac{1}{2}(a_2 \wedge_F b_2) + \frac{1}{2}(a_2 \vee_F b_2), (a_3 \vee_p b_3) \right), 1 \leq i \leq n \tag{2}$$

The plithogenic union is:

$$\tilde{a} \vee_p \tilde{b} = ((a_1, a_2, a_3), 1 \leq i \leq n) \vee_p ((b_1, b_2, b_3), 1 \leq i \leq n) \\ = \left((a_1 \vee_p b_1), \frac{1}{2}(a_2 \wedge_F b_2) + \frac{1}{2}(a_2 \vee_F b_2), (a_3 \wedge_p b_3) \right), 1 \leq i \leq n \tag{3}$$

where

$$a_1 \wedge_p b_1 = [1 - c(v_D, v_1)].t_{norm}(v_D, v_1) + c(v_D, v_1).t_{conorm}(v_D, v_1) \tag{4}$$

$$a_1 \vee_p b_1 = [1 - c(v_D, v_1)].t_{conorm}(v_D, v_1) + c(v_D, v_1).t_{norm}(v_D, v_1) \tag{5}$$

3.2 Neutrosophic set

Florentin Smarandache introduced a new branch of philosophy known as neutrosophy in the year 1980, which studies the origin, nature and scope of entities and also their interactions with different ideational visions. Neutrosophic set is an extension to the fuzzy and IFS which characterise the fuzzy information in the form of truth membership function T, indeterminacy membership function I, and a falsity membership function F (Smarandache 1998, 1999). The three membership degrees (truth, indeterminacy and falsity) enable the neutrosophic set to efficiently handle the inconsistent, uncertain and imprecise information (Abdel-Basset, Manogaran, and Mohamed 2019). The indeterminacy membership function in the neutrosophic set is completely independent of the truth and falsity membership function (Vafadarnikjoo et al. 2018). The important basic definitions of neutrosophic sets are as follows:

Definition 2: Let a universal set X consist of number of elements x such that $x \in X$. A neutrosophic set $A \subset X$, has a truth-membership function $T_A(x)$, indeterminacy-membership function $I_A(x)$ and a falsity-membership function $F_A(x)$ where $T_A(x)$,$I_A(x)$, and $F_A(x)$ are subsets of $]0^{-}1^{+}[$. The summation of membership functions has no constraints and hence $0^{-} \leq supT_A(x) + supI_A(x) + supF_A(x) \leq 3^{+}$.

Definition 3: Let $\tilde{a} = (a_1, a_2, a_3); \alpha, \theta, \beta$ be a single-valued triangular neutrosophic set, with truth-membership $T_A(x)$, indeterminacy-membership $I_A(x)$ function and a falsity-membership function $F_A(x)$ as follows:

$$T_a(x) = \begin{cases} \propto_a \left(\frac{x-a_1}{a_2-a_1}\right) if a_1 \le x \le a_2 \\ \propto_a if x = a_2 \\ 0 otherwise \end{cases} \quad (6)$$

$$I_a(x) = \begin{cases} \frac{(a_2-x+\theta_a(x-a_1))}{(a_2-a_1)} if a_1 \le x \le a_2 \\ \theta_a if x = a_2 \\ \frac{(x-a_2+\theta_a(a_3-x))}{(a_3-a_2)} otherwise \end{cases} \quad (7)$$

$$F_a(x) = \begin{cases} \frac{(a_2-x+\beta_a(x-a_1))}{(a_2-a_1)} if a_1 \le x \le a_2 \\ \beta_a if x = a_2 \\ \frac{(x-a_2+\beta_a(a_3-x))}{(a_3-a_2)} if a_2 \le x \le a_3 \\ 1 otherwise \end{cases} \quad (8)$$

where $\alpha_a, \beta_a, \theta_a \in [0, 1]$, and they represent the highest truth membership degree, the lower indeterminacy membership degree, and the lowest falsity membership degree respectively.

3.3 Neutrosophic AHP

The AHP is a quantitative-based MCDM approach introduced by Thomas L. Saaty in 1970. It is one of the most popular decision-making approaches to solve problems consisting of a large number of criteria. This is because the AHP technique decomposes the problem in a hierarchy with the goal at the topmost level and main criteria and sub-criteria at the intermediate levels. The AHP has the ability to handle both the qualitative as well as quantitative criteria. Previous literature suggests a number of techniques such as ANP, TOPSIS, criteria importance through inter-criteria correlation (CRITIC), stepwise weight assessment ratio analysis (SWARA) for effective decision-making. However, in comparison to these methods, AHP is still preferred because it is well established, simple and easy to understand for the experts, and robust and flexible (Govindan et al. 2015). Despite its robustness, the AHP technique has its own limitations. The normal AHP fails to address the vague and imprecise information. To deal with this situation fuzzy sets were integrated with the traditional AHP. Fuzzy sets are membership functions that the DMs define based on their experience. But, fuzzy sets does not deal with the non-membership function. This issue was addressed by the introduction of IFS (Atanassov 1986).

IFS is an extension of classical fuzzy sets which consists of membership function, non-membership function, and hesitancy degree. However, the indeterminacy function which usually exists in the real case situation and impacts the quality of decision is not dealt with IFS. Indeterminacy means degrees of uncertainty, vagueness, imprecision, undefined, unknown, inconsistency, redundancy. It is a known fact that the world is full of indeterminacy, a more precise imprecision is required. Hence, several extensions to IFS such as neutrosophic set (Smarandache 1995), Pythagorean fuzzy set (Yager 2013), and orthopair fuzzy set (Yager and Alajlan 2017) were then proposed. In this study, AHP technique is applied considering the neutrosophic set. In neutrosophic set an element belongs to the set with a neutrosophic probability, i.e. it is T % true in the set, I % indeterminate (unknown if it is) in the set, and F % false in the set. Further, the plithogenic aggregation operation takes into consideration the degree of uncertainty which otherwise improves the accuracy of the results. Hence, the use of neutrosophic AHP framework under plithogenic environment in this study is justified.

The steps of plithogenic-based neutrosophic AHP framework are described as follows:

Step 1: Divide the complex problem into several sub-problems for easy solving.

Step 2: Construct a hierarchical structure of the problem with goal at the top, main criteria (barriers) at the second level and sub-criteria (sub-barriers) at the third level.

Step 3: Establish a DMs panel $DM = \{D_1, D_2, \ldots, D_k\}; k = 1, 2, \ldots, n$.

Step 4: Let the DMs construct the pair-wise comparison matrix using triangular neutrosophic scale (Table 3).

Step 5: Apply plithogenic aggregation operation to aggregate the k DMs matrix for better accuracy based on the equidistant contradiction degrees between the set of criteria. Using plithogenic aggregation operators the k decision matrix is converted into a single matrix.

Step 6: Computing the crisp values from the aggregated decision matrix by using below equation

$$S(a) = \frac{1}{8}(a_1 + b_1 + c_1) \times (2 + \alpha - \theta - \beta) \quad (14)$$

Step 7: Calculate the local weight of each criteria by first totalling the row values and then carrying out the normalisation process.

3.4 Research framework

This research work analyzes the barriers hindering the adoption of eco-innovation initiatives in the Indian large scale manufacturing industry. Figure 1 presents the brief roadmap of the present study. The step-by-step procedure adopted to attain the objective of the research work is discussed below:

- Identify the eco-innovation initiatives implementation barriers through analysis of previous literature
- Select a case organisation and form a decision-making panel to apply the proposed neutrosophic AHP framework
- Discuss the suitability of the identified eco-innovation barriers with the DMs of the selected case industry. With the inputs from DMs categorise the finalised 28 barriers under five main categories and then build a hierarchy
- Construct pair-wise comparison matrix for main barriers and sub-barriers for $k(k = 1, 2, 3)$ DMs using neutrosophic scale

Table 3. Triangular neutrosophic scale.

Linguistic Variable	Triangular Neutrosophic Scale
Very Weakly Important (VWI)	(0.10,0.30,0.35), 0.10,0.20,0.15)
Weakly Important (WI)	(0.15,0.25,0.10), 0.60,0.20,0.30)
Partially Important (PI)	(0.40,0.35,0.50), 0.60,0.10,0.20)
Equally Important (EI)	(0.65,0.60,0.70), 0.80,0.10,0.10)
Strongly Important (SI)	(0.70,0.65,0.80), 0.90,0.20,0.10)
Very Strongly Important (VSI)	(0.90,0.85,0.90), 0.70,0.20,0.20)
Absolutely Important (AI)	(0.95,0.90,0.95), 0.90,0.10,0.10)

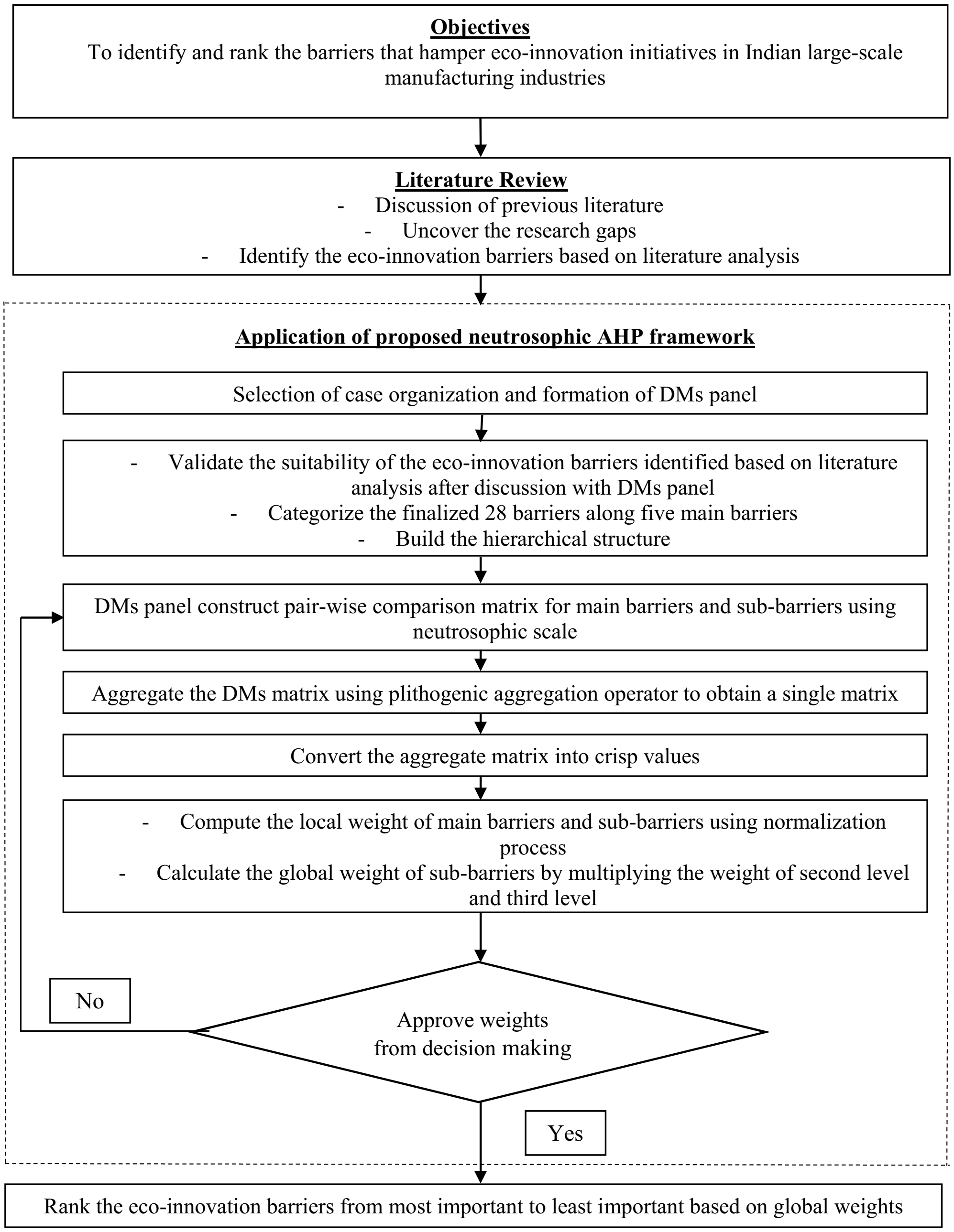

Figure 1. Roadmap of the research.

- Aggregate the *k* DMs matrix using plithogenic aggregation operator to obtain a single matrix
- Determine the crisp values and then compute the local weight of main and sub-barriers through normalisation process. Also, determine the global weight intensity of the sub-barriers
- Rank the sub-barriers based on their global weight intensity

4. Results and discussion

The proposed plithogenic-based neutrosophic AHP approach is applied to a case organisation engaged in the processing and manufacturing of steel.

4.1 Case industry and expert information

In this study, a case industry is selected to apply the proposed plithogenic-based neutrosophic AHP approach. The manufacturing case industry was established in the year 2005 in the western part of India (Gujarat). The case industry is manufacturing automotive body profiles through the processing of steel coils. To do this it has precision manufacturing lines. The case industry has also procured German make advanced blanking lines. The sensitivity of the case industry towards sustainability is evident in the way that several sustainable initiatives are being practiced. The case industry has not only involved itself in environmentally sustainable practices such as reducing carbon emission in transport, sustainable packaging, and energy savings through the adoption of efficient lights but also actively associated in social sustainability activities. Currently, the industry is in the planning to expand their business and improve product quality through collaboration with any world-class foreign manufacturing unit. While doing this the case industry does not desire to compromise with the social and environmental performance rather intends to further enhance its contribution towards sustainability. The managers of the case industry are already of the belief that eco-innovation-focused sustainable initiatives need to be adopted to enhance their sustainable image in the market. However, eco-innovation being a relatively new concept the managers are exposed to several implementation barriers. The objective of the study (ranking of eco-innovation) resulted in the managers feel more confident and hence they agreed to assist in the present research work. The selection of the managers from the case industry for collecting the inputs has a significant influence on the output results. It is of utmost importance that the selected DMs are educated, highly skilled, experienced, and have exposure to the sustainability dimensions. Further the number of experts in the DM panel are finalised based on the literature analysis. Abdel-Baset et al. (2019) applied an integrated ANP-VIKOR for supplier selection problem. They contacted three experts for their analysis. For a project selection problem, Abdel-Basset, Atef, and Smarandache (2019)contacted three experts to apply the hybrid DEMATEL-TOPSIS approach. Hence, for this research work a DMs comprising three experts from different departments of the case industry namely manufacturing, research, and development (R&D) and production, planning, and control (PPC) has been selected for analysis. The demographic profile of the selected DMs group can be found in Table 4.

4.2 Application of plithogenic based neutrosophic AHP framework

In this subsection, the proposed approach is applied to a manufacturing case industry for the analysis of eco-innovation barriers. The application and the results obtained are as follows.

Phase 1: Validating the suitability of the eco-innovation barriers:

In this phase, the suitability of the eco-innovation barriers in the context of the selected case industry is validated. To do this the identified barriers (with description) identified through literature analysis was presented in a questionnaire form to the DMs panel of the case industry. They were asked to confirm whether the identified barriers are relevant to their case organisation. The DMs panel was also authorised to remove any barrier if not suitable and add any barrier if not present in the list. Then with the assistance of DMs panel, the finalised 28 barriers were categorised under five main barriers. Hence, a hierarchical structure is formed wherein the ranking of eco-innovation barriers is at the top, main barriers at the second level, and the sub-barriers at the third level. (Figure 2) presents the hierarchical structure of the present problem.

Table 4. Demographic profile of the decision-making panel.

	Position in organisation	Educational qualification	Experience (years)
Expert 1	Manager (Manufacturing)	B. Tech.	16 Years
Expert 2	Senior Design Engineer (R&D)	M. Tech.	15 Years
Expert 3	Manager (PPC)	DME	15 Years

Phase 2: Calculating the main-barriers and sub-barriers weight using plithogenic based neutrosophic AHP approach

In this phase, the selected DMs group was provided the pair-wise comparison matrix of main barriers and sub-barriers in the questionnaire form (Appendix I). The three DMs recorded their judgements in the pair-wise matrix using the triangular neutrosophic linguistic scale (Table 3). Table 5 presents the pair-wise response obtained from the DMs for the five main barriers. Then, plithogenic aggregation operator based on equidistant contradiction degree of each criterion to the dominant was used to compute the aggregated matrix. The contradiction degree of each criterion to the dominant criteria is as shown in Table 6. The plithogenic aggregation operation increases the accuracy of aggregation. Using Equation 2 the aggregated matrix is computed. Then, the aggregated matrix is converted into crisp value using Equation 14. Lastly, using the normalisation process the criterions local weight is calculated and ranked. The local weight and rank of main barriers are mentioned in Table 7. To determine the crisp value, local weight and rank of sub-barriers a similar process is followed but, not included in the text to manage the word limitation. Table 8 shows the local weight, global weight, and global ranking of the sub-barriers. The global weight of the sub-barrier is the product of the weight of the main barrier and the local weight of the sub-barrier. For instance, the local weight of OMB1 is 0.1862 in the OMB category and the local weight of OMB is 0.1919. The product of 0.1919 and 0.1862 will give the global weight of OMB1.

4.3 Sensitivity analysis

In this study, sensitivity analysis of the eco-innovation barriers rankings has also been performed. There are mainly two reasons to perform the sensitivity analysis, the first is to demonstrate that the rankings of the sub-barriers are sensitive to the weight of main barriers and the second to show that rankings are robust (Ansari, Kant, and Shankar 2020). A sensitivity analysis can be performed either by changing the weights for an expert or by changing the weights of enablers (Munny et al. 2019). This research work performs sensitivity analysis by altering the weights of all main barriers in proportion to the variation of the highest ranked barrier. For experiments 1 to 14, the weight of the EFB (highest ranked barrier) is varied from 0.05 to 0.7 with an increment of 0.05, and accordingly, proportionate changes were made in the other four main barriers. The condition of experiment 15 is EFB weight is kept 0.75 while the weight of the other four main barriers is kept same equalling 0.0625. Table 9 presents the changes in the weight of other barriers due to the variation of EFB weight. The results demonstrate that among the main barriers at 0.05 to 0.25, SB is the top-ranked barrier while, at 0.3 to 0.75 weights, EFB is the most important barrier.

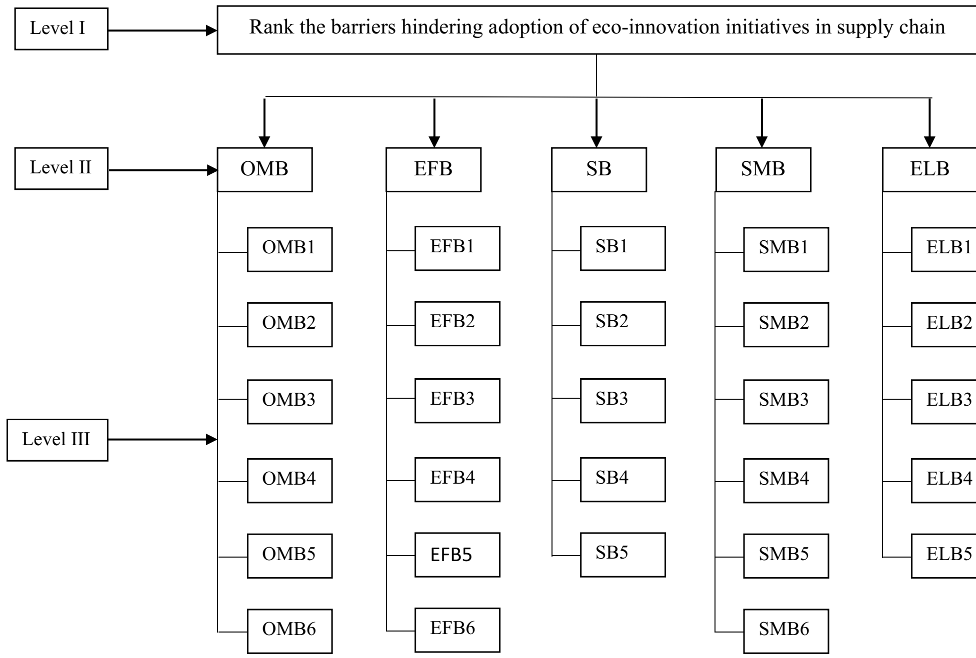

Figure 2. Hierarchy of the considered problem.

Table 5. Pair-wise decision matrix for main barriers.

DM1	OMB	EFB	SB	SMB	ELB
OMB	EI	WI	PI	SI	VSI
EFB	VSI	EI	VSI	VSI	AI
SB	SI	WI	EI	VSI	AI
SMB	PI	WI	WI	EI	SI
ELB	WI	VWI	WI	PI	EI
DM2	OMB	EFB	SB	SMB	ELB
OMB	EI	WI	WI	SI	VSI
EFB	VSI	EI	SI	VSI	VSI
SB	VSI	PI	EI	SI	AI
SMB	PI	WI	PI	EI	VSI
ELB	WI	WI	VWI	WI	EI
DM3	OMB	EFB	SB	SMB	ELB
OMB	EI	VWI	PI	EI	SI
EFB	AI	EI	SI	VSI	VSI
SB	SI	PI	EI	VSI	VSI
SMB	EI	WI	WI	EI	SI
ELB	PI	WI	WI	PI	EI

Table 6. Contradiction degree for main barriers.

	c_1	c_2	c_3	c_4	c_5
Contradiction degree	0	0.2	0.4	0.6	0.8

Table 7. Crisp value, local weight and rank of main barriers.

	OMB	EFB	SB	SMB	ELB	Weight	Rank
OMB	0.495	0.129	0.283	0.685	0.810	0.192	3
EFB	0.617	0.559	0.686	0.795	0.889	0.283	1
SB	0.538	0.260	0.612	0.779	0.920	0.249	2
SMB	0.332	0.103	0.175	0.653	0.776	0.163	4
ELB	0.165	0.127	0.135	0.314	0.677	0.113	5

Table 8. Local weight, global weight and global rank of sub-barriers.

Barriers	Main barrier weight	Sub-barrier	Sub-barrier local weight	Local rank	Global weight	Global rank
OMB	0.1919	OMB1	0.1862	3	0.0357	12
		OMB2	0.2075	2	0.0398	10
		OMB3	0.2352	1	0.0451	7
		OMB4	0.0910	6	0.0175	25
		OMB5	0.1341	5	0.0257	20
		OMB6	0.1459	4	0.0280	19
EFB	0.2834	EFB1	0.2083	2	0.0590	4
		EFB2	0.2395	1	0.0679	1
		EFB3	0.1557	4	0.0441	8
		EFB4	0.1254	5	0.0355	13
		EFB5	0.1884	3	0.0534	5
		EFB6	0.0827	6	0.0234	22
SB	0.2485	SB1	0.2398	2	0.0596	3
		SB2	0.1211	5	0.0301	16
		SB3	0.2703	1	0.0672	2
		SB4	0.2011	3	0.0500	6
		SB5	0.1678	4	0.0417	9
SMB	0.1629	SMB1	0.1224	5	0.0199	24
		SMB2	0.0841	6	0.0137	28
		SMB3	0.1882	3	0.0307	15
		SMB4	0.2344	1	0.0382	11
		SMB5	0.2164	2	0.0352	14
		SMB6	0.1546	4	0.0252	21
ELB	0.1132	ELB1	0.2627	2	0.0297	17
		ELB2	0.1308	5	0.0148	27
		ELB3	0.2519	1	0.0285	18
		ELB4	0.2018	3	0.0228	23
		ELB5	0.1529	4	0.0173	26

Further, the changes in the weights of the sub-barriers due to the variation in the weight of the main barrier is also noted. For EFB weights varying from 0.05 to 0.25, SB3 is the top-ranked sub-barrier. At 0.3 to 0.75, EFB2 is the highest-ranked sub-barrier. The variation recorded in the ranking of other sub-barriers due to changes in the EFB weight from 0.05 to 0.75 is presented in Table 10. Lastly, based on the sensitivity analysis result presented in the table, it is clear that the ranking of the barriers is weight sensitive. Further, the EFB is the most important barrier, and that the ranking of the barriers are not biased rather robust.

Table 9. Changes in the weight of main barriers due to changes in weight of EFB.

Main barrier	Normal (0.2834)	Expt. 1 0.05	Expt. 2 0.1	Expt. 3 0.15	Expt. 4 0.2	Expt. 5 0.25	Expt. 6 0.3	Expt. 7 0.35	Expt. 8 0.4	Expt. 9 0.45	Expt. 10 0.5	Expt. 11 0.55	Expt. 12 0.6	Expt. 13 0.65	Expt. 14 0.7	Expt. 15 0.75
OMG	0.1919	0.2503	0.2378	0.2253	0.2128	0.2003	0.1878	0.1753	0.1628	0.1503	0.1378	0.1253	0.1128	0.1003	0.0878	0.0625
EFB	**0.2834**	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**
SB	0.2485	0.3069	0.2944	0.2819	0.2694	0.2569	0.2444	0.2319	0.2194	0.2069	0.1944	0.1819	0.1694	0.1569	0.1444	0.0625
SMB	0.1629	0.2213	0.2088	0.1963	0.1838	0.1713	0.1588	0.1463	0.1338	0.1213	0.1088	0.0963	0.0838	0.0713	0.0588	0.0625
ELB	0.1132	0.1716	0.1591	0.1466	0.1341	0.1216	0.1091	0.0966	0.0841	0.0716	0.0591	0.0466	0.0341	0.0216	0.0091	0.0625
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 10. Global rank of sub-barriers due to changes in EFB from 0.05 to 0.75.

	Normal (0.2834)	Expt. 1 0.05	Expt. 2 0.1	Expt. 3 0.15	Expt. 4 0.2	Expt. 5 0.25	Expt. 6 0.3	Expt. 7 0.35	Expt. 8 0.4	Expt. 9 0.45	Expt. 10 0.5	Expt. 11 0.55	Expt. 12 0.6	Expt. 13 0.65	Expt. 14 0.7	Expt. 15 0.75
OMG1	12	9	9	9	11	12	13	13	14	14	13	13	13	14	14	18
OMG2	10	5	6	6	7	9	10	11	11	12	12	12	12	12	12	14
OMG3	7	4	4	4	4	6	8	9	9	10	11	11	11	11	11	11
OMG4	25	20	21	24	25	26	25	25	25	25	24	24	21	21	21	27
OMG5	20	17	17	18	19	20	20	21	20	19	19	19	19	18	18	23
OMG6	19	14	14	15	18	19	19	18	18	18	18	17	17	17	16	22
EFB1	4	24	22	16	9	4	3	2	2	2	2	2	2	2	2	2
EGB2	1	23	20	13	5	3	1	1	1	1	1	1	1	1	1	1
EFB2	8	26	26	22	17	11	7	6	4	4	4	4	4	4	4	4
EGB3	13	27	27	26	22	16	11	8	7	5	5	5	5	5	5	5
EFB3	5	25	24	20	12	7	5	3	3	3	3	3	3	3	3	3
EGB4	22	28	28	28	27	24	21	15	12	9	8	7	6	6	6	6
SB1	3	2	2	2	2	2	4	5	6	7	7	8	8	8	8	10
SB2	16	13	13	14	16	17	16	16	16	16	15	15	14	13	13	26
SB3	2	1	1	1	1	1	2	4	5	6	6	6	7	7	7	7
SB4	6	3	3	3	3	5	6	7	8	8	9	9	9	9	9	16
SB5	9	7	5	5	6	8	9	10	10	11	10	10	10	10	10	19
SMB1	24	18	18	21	23	23	24	24	24	23	23	22	22	22	22	25
SMB2	28	22	25	27	28	28	28	28	27	27	26	26	25	23	23	28
SMB3	15	12	12	12	14	14	15	17	17	17	17	18	18	19	19	17
SMB4	11	6	7	7	8	10	12	12	13	13	14	14	15	15	15	12
SMB5	14	8	8	8	10	13	14	14	15	15	16	16	16	16	17	13
SMB6	21	16	15	17	20	21	22	22	22	21	20	20	20	20	20	20
ELB1	17	10	10	10	13	15	17	19	19	20	21	21	23	24	24	8
ELB2	27	21	23	25	26	27	27	27	28	28	28	28	28	28	28	24
ELB3	18	11	11	11	15	18	18	20	21	22	22	23	24	25	25	9
ELB4	23	15	16	19	21	22	23	23	23	24	25	25	26	26	26	15
ELB5	26	19	19	23	24	25	26	26	26	26	27	27	27	27	27	21

4.4 Discussion

The weight intensity as obtained for the main barriers by application of plithogenic-based neutrosophic AHP approach is presented in Table 8. It can be found that barriers related to economic and financial barriers are the most significant factors that hinder the adoption of eco-innovation initiatives. The sequence of the remaining four main barriers are SB-OMB-SMB-ELB. For the successful adoption of eco-innovation initiatives, the economic and financial challenges are very significant.

Under the 'economic and financial barriers' dimension, there are six specific challenges. Based on the analysis, EFB2 obtains the highest rank. Innovation processes are uncertain and would require to allocate more resources than expected for its realisation. Limited availability of internal funds presents an additional challenge to the management to finance the extra cost needed to develop research facilities and allocation of more resources in the innovation process. The EFB1 is the next ranked barrier after EFB2. Geels (2002) suggests that environmental improvement in terms of higher energy efficiency and reduction in carbon emissions can be achieved through the diffusion of novel and clean technologies. However, the high costs involved in the transition to advanced and clean technologies are holding back the management to adopt these technologies. The next ranked barrier based on weight intensity is EFB5. The adoption of eco-innovation initiatives requires high initial investment in terms of creation of skill base, modification in the existing production lines, or procurement of environmentally friendly technologies. Uncertainty associated with the returns on high initial capital investment made in eco-innovation initiatives results in poor commitment from management to eco-innovate. Barriers such as EFB3, EFB4 and EFB6 have obtained low weight intensity and hence less influential.

The 'strategic barriers' category consist of five sub-barriers of which SB3 is the most influential. The diffusion of eco-innovation activities in the entire SC depends on changing the entire infrastructure including the transportation activities (Orji et al. 2019). However, organisations fail to develop an efficient technological infrastructure. The next important barrier is SB1. Collaboration engagement will not only help the organisations to exchange resources, knowledge, and technology among them but also share the risk associated. But, because of cultural differences and especially the fear of sharing their intellectual property with their competitor organisations fail to collaborate. SB4 is the next ranked barrier. Eco-innovation calls for close collaboration between the innovators, financiers, and government bodies during the development phase. The kind of technological competency and cleaner opportunities needed to disseminate eco-innovation initiatives would not be possible due to the failure of active collaboration between the innovators, financiers, and government institutions. The weight intensity of the barriers such as SB5 and SB2 suggests that they are of less importance.

In the 'organizational and management barrier' category, OMB3 is the most important barrier. A proactive corporate strategy clearly stating the economic, social, and environmental goals and changes in organisational structure with clear distribution of sustainable responsibilities is necessary to engage in eco-innovation activities (Visser, Jongen, and Zwetsloot 2008). Hence, it is challenging for organisations. The second most important barrier is OMB2. Eco-innovation initiatives especially involve technological skills that reduce the environmental impacts and enhance competitiveness. Unavailability of sufficient human capital base in terms of eco-design expertise, trained operators for clean technologies, and inability to understand the cleaner production processes deters the organisations to adopt eco-innovation initiatives (Montalvo 2008). The next barrier in line is the OMB1. Insufficient availability of highly committed top-level managers having a high degree of self-efficacy and leadership qualities fail to do proper market research and develop appropriate models to acquire information regarding novel environmental technologies. The barriers such as OMB6, OMB5 and OMB4 have the least influence on the adoption of eco-innovation initiatives.

The 'social and marketing barriers' dimension consists of six sub-barrier of which SMB4 is the topmost ranked barrier. Consumer willingness to pay a premium amount for the environmentally friendly products/cleaner products motivates the organisations to adopt eco-innovation initiatives (Carrillo, del Río González, and Könnölä 2009). But, most of the developing countries comprise a higher percentage of low-income class, and hence the innovative products which are usually costlier than the normal products receive poor response from the customers. The next ranked barrier is the SMB5. Eco-innovations activities in an organisation can be encouraged through changes in organisational culture and adopting a proactive approach to diffuse sustainable dimensions. However, the cultural inertia of the organisation to continue with the same old traditional process as they have been doing in the past deters the adoption of eco-innovation initiatives. SMB3 is the next ranked barrier. Organizations would be forced to engage in eco-innovation initiatives if there is demand for environmentally conscious products from consumers or policy-makers/NGOs monitor the environmental damage created by the manufacturing operations. However, organisations in developing countries do not feel sufficient pressure to innovate because of poor demand for innovative products and lack of environmental policy. SMB6, SMB1 and SMB2 are the other least important barriers. The environmental and legal barriers have the least influence on the adoption of eco-innovation initiatives.

4.5 Implications of the study

4.5.1 Theoretical implications

The key theoretical implications of the present research work are as follows:

(1) This research work evaluates the barriers hindering the adoption of eco-innovation initiatives for the large-scale manufacturing industries in the context of developing countries. While several studies in the literature could be found that investigate eco-innovation adoption barriers but, a research contribution in the context of developing countries especially large-scale manufacturing industries is limited. The findings obtained in the context of developed countries may not be suitable for the developing countries because of dissimilar socio-economic conditions. Hence, this inadequacy in the research is filled by the present study by investigating the eco-innovation barriers for large-scale manufacturing industries specifically in the context of developing countries.
(2) This study initially identifies the eco-innovation barriers through analysis of relevant literature and then finalise it after validating with the DMs panel of the selected case manufacturing industry. Further, the present study not only identifies the barriers but also analyse and compute the weight intensity of each barrier.
(3) A novel plithogenic based neutrosophic AHP approach is used in this research work to rank the barriers. This approach has the ability to handle the inconsistent and uncertain human inputs thus enabling higher accurate results.
(4) The ranking of the barriers will help the policy-makers of the case industry feel more confident in their decision-making. It will aid the managers to develop appropriate strategies for each barrier starting from a highly important barrier to the least important barrier to mitigate its effect.

4.5.2 Managerial and social implications

The findings of the study present important implications to the managers/practitioners of large-scale manufacturing industries engaged in the implementation of eco-innovation initiatives. The managers must eradicate the barriers for effective adoption of eco-innovation initiatives in the SC. The analysis and ranking of barriers will help the managers to identify which barriers need more focus and which barriers need less focus in their organisation. Eco-innovations are complex and their adoption would require major changes in the traditional SC of the organisation. The knowledge regarding the severity of each barrier will assist the top management to undergo radical structural changes in the organisation's culture. The results of the study would encourage the industrial managers to adopt a proactive approach in the adoption of eco-innovation initiatives and alteration of existing policies. To diffuse eco-innovation initiatives in the traditional SC is a costly affair as it needs additional funds for allocation of more resources, create R&D facilities, and transit to cleaner technologies. This research suggests the top management to arrange for additional funds for the adoption of eco-innovation practices. The high initial investments of eco-innovation would be recovered by the long-term benefits realised due to its adoption. Hence, it is necessary for the practitioners that they efficiently allocate available limited funds so that the other SC activities are not compromised.

The present study also presents several social implications. The markets of the developing nations are usually cost conscious and hence the demand for eco-innovative products which are often costly is less. However, creating awareness amongst the consumer regarding the environmental benefits realised due to adoption of eco-innovative products would influence their buying decision. Consumer's perception that eco-innovative products are low grade in quality because of the use of recycled material needs to be changed through promotions. Also, workforce should be motivated so that they overcome their cultural resistance to change and move towards adoption of novel energy-efficient technology.

5. Conclusion

The rising environmental and social consciousness coupled with market competitiveness has resulted in increased pressure on the manufacturing industries that they transit and find novel and sustainable ways for taking their businesses ahead. Eco-innovation has emerged as a popular sustainable approach which not only helps the present SC become economically sustainable but also environmentally and socially responsible. But, the path to the adoption of eco-innovation initiatives especially in the developing countries is not that easy as expected. Several barriers exist on the way of diffusion of eco-innovation initiatives in the traditional SC. Hence, the present study is an attempt to identify and analyse the potential eco-innovation barriers in the SC. The basic objective behind conducting this study is to rank the barriers hindering the adoption of eco-innovation initiatives in the SC in developing countries. This research is motivated because of limited research on analysis of eco-innovation adoption barriers for large-scale manufacturing industries in the context of developing countries using a plithogenic based neutrosophic AHP approach.

From the five main barriers 'economic and financial barriers' are the most influential barriers followed by 'strategic barriers'. The 'organizational and management barriers' are in third place. 'Social and market barriers' and 'environmental and legal barriers' stand at fourth and fifth place respectively. Based on the global weight of sub-barriers 'lack of internal funds necessary to meet the extra cost and R&D cost' is the most important barrier. The other influential barriers in order of importance are 'absence of complementary assets (such as infrastructure, standards)', 'lack of collaboration agreements with other organizations', 'high costs involved in the transition to new technologies', and 'uncertain returns on eco-innovation investment'. The robustness in the ranking of the eco-innovation barriers is checked by performing sensitivity analysis. The findings of the study may aid the managers or policy-makers to identify the most important barriers hindering the adoption of eco-innovation initiatives. The proper and clear understanding of the impact of each eco-innovation adoption barrier will enable the policy-makers to eradicate them in the initial phases of implementation by formulating an appropriate action plan. The organisation need to adopt strategies/solutions to mitigate the barriers and enhance the adoption rate of eco-innovation initiatives. Adoption of knowledge management concept and improving the knowledge transfer across the supply chain activities would help organisation overcome the barriers. Better transfer of knowledge would enable effective flow of information internally as well as externally. Organization also need to invest in novel technologies, collaborate with other manufacturing units and develop efficient technological infrastructure to reduce the eco-innovation barriers.

The summary of the main contributions of this research work is as follows:

- This research work contributes to the existing knowledge body of eco-innovation by identifying 28 barriers hindering adoption of eco-innovation initiatives in large-scale manufacturing industries SC in the context of developing countries.
- This study validated the suitability of the identified barriers by discussing them with the DMs panel of the selected manufacturing case industry. The inputs from the DMs panel were also taken to categorise the identified 28 sub-barriers along five main categories.
- The novelty of the present research work is that this study applied a novel plithogenic based neutrosophic AHP approach to rank the eco-innovation barriers. Neutrosophic set is an extension to the fuzzy and IFS and it not only has the ability to handle the inconsistent and imprecise information but also efficiently handles the uncertain information. Further, the use of plithogenic aggregation operators to aggregate the inputs of DMs panel increases the aggregation accuracy.
- The proposed framework presents several theoretical and practical implications that will aid the policy-makers/practitioners of the developing countries in developing strategies to mitigate the eco-innovation adoption barriers.

The study has certain limitations and recommendations for future research work. To attain eco-innovation for sustainability in the SC several aspects have to be considered, and hence barriers management has been analysed in this study. Thus, future research should investigate the other aspects to enhance the adoption rate of eco-innovation using the proposed approach to improve the sustainability of the SC. The results of the study solely depend on the inputs from the DMs panel and hence the entire process of evaluation has to be carried out with extreme care. Also, the findings are region specific, i.e. Indian context in Asia. However, the results of a similar type of study may vary from region to region. Hence, a regional-based comparative study can be conducted in future. Development of an expert panel group from different similar type of industries is an another avenue for future research. Further, the analysis of the data using plithogenic-based neutrosophic AHP involves complex mathematical calculations in comparison to the classical AHP approach. Hence, future research should develop a user-friendly solver which will enable its vast application for finding solution to other real case problems. This study has combined plithogenic operator with AHP to evaluate the barriers hindering eco-innovation initiatives. Hence, future researchers can integrate plithogenic operator with other MCDM techniques such as plithogeny-ANP, plithogeny-SWARA, plithogeny BWM, to evaluate the considered problem. The proposed approach can be used to solve any other problem having multiple criteria. Lastly, the authors plan to extend the present work by identifying and analysing the solutions to mitigate the eco-innovation barriers by integrating the plithogenic based neutrosophic set with any other MCDM technique.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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