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RESEARCH ARTICLE

Evaluating critical barriers and pathways to implementation of e-waste formalization management systems in Ghana: a hybrid BWM and fuzzy TOPSIS approach

Dehu Chen[1] · Daniel Faibil[1] · Martin Agyemang[2]

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Abstract
The majority of developing countries are facing enormous challenges in implementing sustainable waste electrical and electronic equipment (e-waste) management systems. Informal e-waste management practices in Ghana have become a critical challenge to the government and the various stakeholders owing to its environmental and health impacts. However, the effort to implement e-waste formalization management practices has been threatened with many barriers. This study aims to identify and evaluate barriers and pathways to the implementation of e-waste formalization management systems in Ghana. A three-phase methodology consisting of the Delphi method, the hybrid best–worst method and the fuzzy TOPSIS technique is employed. The first phase involves extensive literature review and the use of the Delphi method to identify barriers, pathways, and data collection for e-waste formalization. In the second phase, the best–worst method was employed to analyze the relative weight and ranking of the barriers. The third phase involves the application of fuzzy TOPSIS to rank and prioritize pathways to e-waste formalization systems. Fuzzy logic was applied to handle the subjectivity of decision-makers' preferences. A sensitivity analysis was carried out to check the robustness of the framework and address any effect of bias. The outcome of the study indicates that economic and financial limitations are the most significant barriers to e-waste formalization. "Setting up resourced environmental government agencies for effective monitoring and auditing at the regional levels for appropriate e-waste management practices" is the most prominent pathway. The present study can potentially inform policy makers to develop systematic and strategic policies for the implementation of e-waste formalization management systems.

Keywords E-waste · Formalization · Informal · Barriers · Pathways · Best–worst method · Fuzzy TOPSIS

Introduction

Presently, waste electrical and electronic equipment (e-waste) is regarded as one of the fastest-growing waste stream due to population growth, urbanization, technological advancement, and consumers' insatiable appetite for new electronic products (Qu et al. 2019). E-waste is a complex mixture of hazardous and nonhazardous materials that require specialized processes of collection, transportation, segregation, treatment, and disposal (Wang et al. 2017). It has been suggested that approximately 50 million metric tonnes (Mt) of e-waste are produced worldwide every year, with a projection to double increase by 2050 (StEP 2017). E-waste contains substantial varieties of valuable materials such copper, aluminum, platinum, gold, and silver, among others, which can be recovered and put back into reuse (Islam and Huda 2020a); also, it contains substantial noxious materials like toxic trace metals, persistent organic pollutants (POPs), brominated flame retardants (BFRs), heavy rare earth metals, and polychlorinated dibenzo-*p*-dioxins (PCDDs), which poses a significant threat to human health and the environment when they are improperly managed and disposed (Islam and Huda 2020a; Xu et al. 2014).

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✉ Dehu Chen
chendh@dlut.edu.cn

Daniel Faibil
dfaibil@gmail.com

Martin Agyemang
martinon463@gmail.com

1 School of Management and Economics, Dalian University of Technology, Dalian, Liaoning Province, People's Republic of China

2 New Huadu Business School, Minjiang University, Fuzhou 350108, Fujian Province, People's Republic of China

Globally, the informal means of managing e-waste have been observed as major practices that release hazardous substances, which accounted for the adoption and implementation of e-waste formalization management practices in many developed economies (Schumacher and Agbemabiese 2019; Wang et al. 2017). The formalization of e-waste management practices is described as the deployment of skilled labor, state-of-the-art technologies, innovative systems, and process having the capacity to recover e-waste components without dreadful consequences on the ecosystem and human health (Qu et al. 2019). According to the United Nations Environmental Program (2019), about 85% of e-wastes generated worldwide are recycled through informal practices in developing countries such as Ghana, Nigeria, Kenya, India, and Vietnam, among others. The informal means of managing e-waste is described as all antiquated practices applied by unauthorized e-waste recyclers through the burning of wires in the open air, heating plastics and circuit boards, manual dismantling, and spilling of corrosives to recover valuable e-waste components (Tong et al. 2018).

The implementation of sustainable e-waste management practices in Ghana continues to remain a critical challenge in the Ghanaian e-waste industry. Ghana annually imports 40,000 t of e-waste, making Ghana one of the major hubs of e-waste in Africa (Oteng-Ababio 2012). It is estimated that 95% of these imported e-wastes are managed through informal practices, which endangers the environment and human health (Feldt et al. 2014). E-waste management practices in Ghana are carried out across the country. However, Agbogbloshie is the most important informal e-waste dumping site in Ghana (Oteng-Ababio et al. 2016). Informal e-waste management activities in Agbogbloshie result in the generation of a huge amount of solid wastes that pollutes the environment with hazardous health implications. Previous studies have highlighted that informal e-waste operators, surrounding communities, and residents at e-waste dumping zones in Ghana easily contract and spread disease such as chronic gastritis, duodenal ulcers, skin damage, headaches, vertigo, and nausea (Kaifie et al. 2020; Oduro-Appiah et al. 2017; Oteng-Ababio et al. 2016). With the increasing dangers associated with informal e-waste management practices in Ghana, the government, environmentalists, industry actors, and various stakeholders have raised concerns about implementation of e-waste management and disposal to safeguard the environment and human lives. The implementation of formal management practices has been threatened with numerous challenges. A plethora of studies (Feldt et al. 2014; Mudge et al. 2019; Oteng-Ababio 2012) conducted on e-waste management in Ghana concentrated mainly on the health risk associated with informal e-waste management practices, and studies evaluating factors obstructing e-waste formalization management are rare. Therefore, motivated by informal e-waste management practices and its environmental, health, and socioeconomic implications in Ghana, this study aims to fill the research gaps by identifying and analyzing critical barriers and appropriate pathways to the implementation of e-waste formalization management practices. Hence, this study is premised on the following research objectives:

1. To develop a framework to identify critical, sub-barriers, and applicable pathways impeding e-waste formalization adoption and implementation
2. To prioritize and rank both barriers and pathways for strategic and systematic implementation of e-waste formalization management practices
3. To recommend the study's implications to facilitate e-waste formalization management practices

The objectives of the study are achieved through a three-phase methodology involving a Delphi method and a hybrid multi-criteria decision-making (MCDM) technique comprised of the best–worst method (BWM) and fuzzy technique for order preference by similarity to ideal solution (fuzzy TOPSIS) to evaluate the barriers and the pathways. The Delphi method helps in ascertaining the views of experts on the significance of factors/criteria/attributes, aids in prioritization, and also helps in policy formulation to facilitate future predictions through consensus building (Ahmad and Wong 2019; Kauko and Palmroos 2014). The BWM technique was used to analyze and prioritize the relative weight of the barriers, while the fuzzy TOPSIS technique was employed to evaluate and to rank the applicable pathways with respect to the sub-criteria. The BWM was selected over other MCDM techniques on the basis that the BWM provides a high level of consistency; it has less number of pairwise comparisons; it is straightforward to compute; and it provides an unbiased, transparent construction process which makes it is easy to comprehend by decision-makers (Badri Ahmadi et al. 2017; Gupta 2018a, b; Gupta and Barua 2017; Kannan et al. 2020; Kheybari et al. 2019; Lo et al. 2018; Malek and Desai 2019; Pour et al. 2019; Rezaei 2015).

Also, the fuzzy TOPSIS technique is employed in this study because it provides enormous advantages over other MCDM methodologies. The technique has been widely applied in many studies in different fields (Chen 2000; Guo and Zhao 2015; Gupta and Barua 2018b; Liu and Wei 2018; Zyoud et al. 2016). TOPSIS provides a simple and understandable platform for arranging and decomposing decision problems involving many attributes. TOPSIS is limitless to the number of factors for a study; its logic is rational and easy to compute (Govindan et al. 2013; Gupta and Barua 2018b). Nonetheless, decision-making with the classic TOPSIS technique is insufficient to address vagueness, subjectivity, and incomplete information (Agrawal et al. 2016). Given the limitations of the TOPSIS technique, we integrate the fuzzy set theory to deal with uncertainty, ambiguity, and nonobtainable or partial information under a fuzzy environment (Guo and Zhao 2015; Gupta 2018b).

Building on the previous literature, the study contributes to existing studies in three ways. First, it provides new insights regarding levels to identify and evaluate barriers and pathways for e-waste formalization management practices through the Delphi method and MCDM. Additionally, the hybrid application of BWM and fuzzy TOPSIS techniques for analyzing and ranking of both the barriers and the pathways gives foundation for understanding important and less important criteria by decision-makers. Furthermore, the study provides insights into applying models and procedures in an integrated approach and, particularly, the application of BWM and fuzzy TOPSIS techniques for rating e-waste management problems. Moreover, the study presents knowledge to enable policy makers comprehend and prioritize the best strategies to enhance in developing systematic and strategic policies for sustainable e-waste management.

The rest of the paper is structured into four sections. The first section focuses on literature review by introducing the literature and identifying the existing research gaps related to e-waste barriers and pathways for e-waste formalization management implementation as well as the methodological concerns of MCDM application. The "Research methodology and data collection" section presents the methods and data collection used in the study. Subsequently, the results and findings of the study are presented in the fourth section. The fifth section focuses on the discussion of the study with attention given to the sensitivity analysis and the theoretical contribution and implications. The conclusion, limitations, and opportunities for future studies are presented in the last section.

Literature review

This section introduces the theoretical foundation of the study, the significance of MCDM techniques in e-waste management, and barriers and pathways for e-waste formalization management implementation as well as research gap.

Theoretical background

The interminable advancement in information technology and the growth in electronic markets have resulted in the folded production of e-waste in recent years. The annual e-waste generation was estimated between 40 and 50 Mt as of 2018, which is projected to upsurge to 55.2 Mt by 2021 (Islam and Huda 2020a; Sarc et al. 2019). Guo and Yan (2017) posited that a substantial proportion of e-wastes is generated in the developed countries due to their growth and expansion in technology, information, and internet usage. China is projected to lead in the generation of e-waste with an estimated 16.5 Mt, followed by the European Union, USA, and Japan (Qu et al. 2019). The shipment of e-waste to developing countries is the result of stringent policies and well-structured methods for recycling e-waste in the developed countries (Li et al. 2020). The continuous flow of e-waste from the developed countries to developing countries is the result of availability of cheap labor, noncompliance of international conventions (such as Basel Convention, the Busan Pledge for Action on Children's Environmental Health of 2009, and the Strategic Approach to Integrated Chemical Management's expanded Global Plan of Action issued at the International Conference on Chemical Management ICCM3 in 2012), unemployment, economic challenges, and lack of infrastructure, among others (Wan et al. 2016).

Informal e-waste management practices significantly affect the environment and human health. However, it is extensively practiced in many developing countries in Asia and Africa (Asamoah et al. 2018; Wang et al. 2017). Prior studies have revealed that informal e-waste management practices can damagingly induce the environment and spread diseases (Feldt et al. 2014; Tue et al. 2016). For example, Itai et al. (2014) used portable X-ray fluorescence spectrometer (P-XRF) to assess the adverse effects of informal management practices on the environment by metal(loids) and organic pollutants. Tue et al. (2016) also employed the graph and stakeholder theory to determine how the use of harmful chemicals and open-air burning of wires and plastics at informal e-waste sites affect the health of e-waste operators and surrounding communities.

Even though adopting formalization systems in managing e-waste is uncommon in developing countries, existing studies underscore the importance. Yong et al. (2019) evaluated electronic waste management strategies and recycling operations in Malaysia and proposed that hefty import levies should be imposed on the importation of second-hand electrical products to dissuade the importation of such products. They discuss the significance of paying subsidies and incentives to existing recovery facilities and scrap collectors for transportation to accredited facilities for recycling. Kiddee et al. (2013) present a generalized overview of toxic substances present in e-waste and their potential environmental and human health impacts together with management strategies currently being used in certain countries. The purpose of the study was to evaluate the appropriate e-waste management tools, namely, life cycle assessment (LCA), material flow analysis (MFA), and multi-criteria analysis (MCA), tools to manage e-waste problems, and the extended producer responsibility (EPR) approach. They proposed that the most effective ways to address e-waste management are to develop an eco-design device and effective and proper collection systems, apply safe methods for recycling/management, create awareness of the impact of e-waste, and dispose e-waste through proper techniques as well as ban the shipment of used electronic products. The study revealed that all decision-making tools should complement each other to enhance effective e-waste management.

Wang et al. (2016) assessed driving factors that impact the intentions of resident participation in informal e-waste management practices using the theory of planned behavior and structural equation modeling and established that e-waste collection centers are a major factor in developing countries. Nnorom and Osibanjo (2008), on the other hand, presented an overview of the EPR concept in electronic waste management practices, legislations, and their applications in developing countries (Nigeria). The study described that the lack of adequate infrastructure, change in government attitude, lack of appropriate legislation dealing specifically with e-waste, lack of practicing the EPR concept, and nonenforceability of transboundary policies are the key factors impeding effective management of e-waste in developing countries. The study established that there must be an introduction of both government-driven (authorized) and industry-driven (voluntary) EPR programs in developing countries to check and control immense environmental contamination through illegal e-waste management. Thavalingam and Karunasena (2016) applied an integrated framework and multiple case studies approach to identify gaps and stakeholder involvement in mobile phone e-waste management in Sri Lanka and established major gaps in legislation and processes, public contribution, e-waste, lack of policies and strategy stimulation, and inadequate awareness of indiscriminate disposal impacts. They stated that imposition of an annual tax on all registered importers and mobile phone accessories, the identification and ban of mobile phone types that have a higher content of hazardous material, and setting acceptable standards for recycling are critical measures to address e-waste management in Sri Lanka.

Kumar and Dixit (2018a) applied interpretive structural modeling (ISM) and decision-making trial and evaluation laboratory (DEMATEL) to evaluate the hierarchal and contextual relationship structure among the barriers of e-waste management in India. They revealed that, the lack of public awareness about e-waste recycling and the lack of policies addressing e-waste issues are the root cause barriers. They concluded that the elimination of these barriers would automatically expunge all the other barriers. Solomon (2010) indicated that environmental ethics, environmental laws, and environmental education are three crucial disciplines essential for protecting the environment and human health against the illegal management of e-waste. Kim et al. (2013) explained that recycling technology and extended producer responsibility would help in smooth e-waste collection, segregation, and recycling, and this will afford producers to develop eco-friendly sustainable products. Ikhlayel (2018) explained that the application of integrated models and policies can improve e-waste management by addressing critical issues from the regional levels simultaneously. The study further postulated that all key stakeholders can ensure the attainment of efficient and effective e-waste management when they operate as a team and share information that will aid in the tracking exportation and importation of electronic products from various jurisdictions.

Sarkhel et al. (2016) concluded that appropriate e-waste can be achieved when there is availability of sufficient e-waste transport systems, infrastructure, skilled labor, recycling plants, and involvement of environmental advocacy agencies at the regional and national levels. Nduneseokwu et al. (2017) applied the theory of planned behavior (TPB) to assess critical factors influencing consumer's intension and lack of involvement in formal e-waste management in Nigeria. The findings revealed that consumers' attitude, infrastructure, and lack of environmental awareness contribute vastly to consumer's inability to participate in e-waste management. It was suggested that e-waste management education, incentives, and awareness programs should be carried out by media practitioners and environmental advocacy groups at the community level to drive the interest of consumer's participation in e-waste management. Chi et al. (2011) highlighted that enhancement and integration of standard e-waste management depends significantly on three perspectives (economic, social, and technical). For example, it provides an alternative livelihood to informal operators, financial support, appropriate skills, tools and technology, etc. Orlins and Guan (2016) also found that the majority of household auctions their e-waste products to individual private collectors, which are passed on in the informal recycling process due to consumers' reluctance to pay for recycling charges. The study suggested that manufactures and nongovernmental organizations can succor in enlightening consumers and informal operators about appropriate approaches they can apply to enhance their activities to deal with health, environmental, and socioeconomic implications. To this end, strategic understanding and awareness about the implementation of appropriate e-waste management systems will bring desirability and improve the economic development, urban mining, and poverty alleviation in developing countries or economies (Garlapati 2016).

E-waste formalization management implementation: barriers

Barriers related to media roles in environmental awareness (BM_1)

The media involvement in addressing environmental issues is critical in ensuring a green environment (Suh et al. 2019). Sub-barriers are poor media coverage on informal management of e-waste and low level of media advocacy on implementing formalization of e-waste (Cucchiella et al. 2015; Sirisawat and Kiatcharoenpol 2018).

International trade treaties (transboundary) (TB_2)

Here, the ever-growing requirements in developed countries create a setback for an economically viable and friendly environment for e-waste operation (Milovantseva and Fitzpatrick 2015). The sub-barriers are unemployment in developing countries; lack of clear definition of e-waste, affecting the implementation of transboundary treaties (conventions) (Bakhiyi et al. 2018); lack of information dissemination, statistics, and resources among countries to identify functional e-wastes at the various ports; and lack of political commitment in developing countries to implement stringent measures for an e-waste formalization (Daum et al. 2017; Sirisawat and Kiatcharoenpol 2018).

Economic and financial limitations (EFL_3)

Economic and financial constraints affect the adoption and commencement of formal approach of managing e-waste (Bhatia and Srivastava 2018). Sub-barriers include the lack of securing government subsidies and financial support (Malek and Desai 2019); lack of funds for training and awareness program (Liu et al. 2015); high transformation costs, affecting the adoption of modern techniques (Islam and Huda 2018); lack of resources to invest in recycling machineries; and high cost of properly disposing waste (Khan 2016).

Lack of environmental laws and regulations ($LELR_4$)

Environmental laws and regulations at the national land local levels are said to be a crucial layout to the adoption and implementation of formal e-waste management practices. Strategic and strict government environmental policies will strengthen formal e-waste management practices (Bhatia and Srivastava 2018). The sub-barriers are delay in the formulation and enforcement of e-waste formalization law, government's inability to formulate specific policies in the formalization of e-waste, lack of policies and regulation toward environmentally sound e-waste management, and lack of systematic monitoring and auditing of government institutions (Islam et al. 2019; Wang et al. 2017).

Lack of formal e-waste collection points/centers ($LFEWCP_5$)

The nonexistence of formal e-waste collection points/centers has resulted in the influx of informal e-waste collectors due to their accessibility which has led to the expansion of the informal e-waste sector (Wang et al. 2017). The sub-barriers are the lack of effective and acceptable collecting models (Wang et al. 2017), high costs of running site rent and employee recruitment, and the fear of competitive advantages related to informal collectors (Zeng et al. 2017).

Lack of public education about informal e-waste management practices ($LPEW_6$)

The lack of effective public awareness about the threats the informal approach of e-waste management practices poses to human health and the environment is a critical barrier in the implementation of e-waste formalization (Li et al. 2020).The sub-barriers include the lack of public awareness toward e-waste management, inadequate support and training program for unskilled labor (Heacock et al. 2016), lack of training and risk awareness on informal management (Islam et al. 2019), adoption of throwaway behaviors rather than acquiring a replacement by consumers (Baxter et al. 2016), and lack of awareness of business opportunities about the formalization of e-waste management (Orlins and Guan 2016).

Lack of external environmental entity and reformist participation ($LEEP_7$)

The lack of skilled professionals' involvement to formal approach of e-waste practices is significant to the e-waste industry (Tong et al. 2018). Sub-barriers include lack of partnership with nongovernmental organizations (NGOs), development agencies, and local government in e-waste management (Malek and Desai 2019); lack of green management practices education by external entities for informal e-waste workers (Rajesh Ejiogu 2013); lack of pressure from stakeholders in formalization e-waste sector; and lack of communication with external partners and poor role clarity (Tong et al. 2018; Tue et al. 2016).

Lack of appropriate infrastructure ($LAIF_8$)

The availability of an appropriate infrastructure system plays a significant role in stimulating proper management practices in the e-waste industry. An appropriate infrastructure in place enhances the implementation process of formal e-waste management practices (Lawhon 2012). Relevant sub-barriers include the lack of storage, transportation, treatment, and disposal technology facilities (Guerrero et al. 2013); lack of logistics for proper auditing and monitoring (Feldt et al. 2014); lack of technology to apply restriction of hazardous substances (RoHS) policies; and poor planning and projections of e-waste importation and generation (Agyemang et al. 2018; Islam and Huda 2020a).

Barrier related to extended producer responsibility (EPR_9)

The role that electronic and electrical companies/producers/manufacturers play is crucial in addressing informal e-waste management practices. The lack of producer/manufacturer responsibility to take back unwanted and faulty e-waste products contributes hugely to formal e-waste management practices (Guerrero et al. 2013). The sub-barriers include the lack of corporate social responsibility of producers (willing to consider consumer consequences during and after product usage), high cost of recycling e-waste equipment for reuse (Wang et al. 2017), and lack of cooperation between consumers and manufacturers (Julander et al. 2014).

Pathways to e-waste formalization management systems

The literature suggests several pathways which can help in the adoption and implementation of a formal approach to managing e-waste. These pathways require unwavering commitment and support from the government, industry players, and various stakeholders in the e-waste industry locally and globally. Therefore, Table 1 presents the pathways to the implementation of a formal approach to e-waste management practices in Ghana.

The application of the multi-criteria decision-making technique

MCDM techniques simplify the selection and prioritization of factors/criteria in a complex system. MCDM techniques are best applied when a larger number of factors/criteria influence the performance of a system (Gupta and Barua 2017). E-waste management in the past decades has become a complex and challenging concern that requires various opinions to surmount. A number of MCDM techniques have been developed to support DMs (decision-makers) in their judgment (Běhounek and Daňková 2019). In order to determine and address the complexity in the decision-making process, MCDM techniques provide assessment tools that enable DMs to rate their preferred criteria over equally viable available criteria/factors (Wu et al. 2019). MCDM offers support to DMs which helps in prioritizing and establishing a significant relationship among the decision-making criteria/factors (Sirisawat and Kiatcharoenpol 2018). Over the years, MCDM techniques have been widely employed in various fields of study. Satapathy (2017) employed ISM to analyze the relationship between the barriers influencing plastic waste management. Malek and Desai (2019) applied BWM to analyze sustainable remanufacturing barriers in the electronic industry in India. Other studies applied hybrid MCDM techniques to resolve concerns in e-waste management. For instance, Ahmed et al. (2016) employed a hybrid analytical hierarchy process (AHP) and DEMATEL to determine the weights and causal relationships among the criteria for sustainable end of life (EoL) vehicle assessment. Kumar and Dixit (2019) used novel hybrid MCDM techniques of fuzzy AHP and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) to evaluate selection criteria of recycling

Table 1 Pathways to the implementation of e-waste formalization management practices

Pathways	Reference
1. Provision of infrastructure by government for modern e-waste management (P_1).	Islam et al. (2019)
2. Designing of valid, effective policies and roadmap by government and policy makers to reduce environmental degradation (P_2).	Xu et al. (2012)
3. Effective implementation of transboundary conventions (Basel Ban amendment) on e-waste (P_3).	Tong et al. (2018)
4. The introduction of green management practices for handling e-waste (P_4).	Wang et al. (2016)
5. Engagement of skilled workforce by e-waste entrepreneurs (P_5).	Oteng-Ababio (2012)
6. Effective proper coordination or collaboration between government and operators for smooth formalization of the informal management of e-waste (P_6).	Daum et al. (2017)
7. Effective and efficient public awareness creation toward e-waste recycling (P_7).	Heacock et al. (2016)
8. Stringent punishment should be meted out by regulatory authorities to enforce e-waste formalization (P_8).	Cucchiella et al. (2015)
9. Provision of technical assistance and capacity-building programs for informal e-waste management workers (P_9).	Wang et al. (2017)
10. Producers should practice take-back policies (P_{10}).	
11. Setting up resourced environmental government agencies for effective monitoring and auditing at the regional levels for appropriate e-waste management practices (P_{11}).	Kumar and Dixit (2018b)
12. Creation of a common platform where information on formal e-waste management practices are accessible (P_{12}).	Wang et al. (2017)
13. There should a broader consultation, collaboration, and partnership between operators and stakeholders (P_{13}).	Woo et al. (2016)
14. Training informal e-waste entrepreneurs and managers on new technology and the type of expertise required in formalizing the sector (P_{14}).	Fujimori et al. (2016)
15. Government should provide tax cuts, incentives, and technical assistance to enable informal e-waste recyclers, to adopt a formal management system (P_{15}).	Sthiannopkao and Wong (2013)

partners on the basis of green competencies. A wide range of studies have employed MCDM techniques to address e-waste management problems (Islam and Huda 2018; Wu et al. 2013). Nevertheless, the application of MCDM to evaluate factors affecting sustainable e-waste management especially formal e-waste in Ghana's e-waste industry is rare. Therefore, this study employs a hybrid BWM and fuzzy TOPSIS to analyze critical barriers and pathways for the implementation of e-waste formalization management systems.

Research methodology and data collection

In this section, we discuss the research methods, the three-phase methodology (Delphi method, BWM, and fuzzy TOPSIS) employed for the study as shown in Fig. 1, and details of data collection for the analysis and ranking of barriers and pathways to the implementation of e-waste formalization management.

Delphi method

The Delphi method is useful in addressing complex situations, it gives policy direction as well as it help in making future predictions, and it works by obtaining expert opinion through comprehensive discussion till the final consensus is built (Dalkey and Helmer 1963; Schumacher and Agbemabiese 2019). In achieving consensus on complicated issues, a team of experts in a particular field of study with much experience is considered to evaluate the criteria (Gupta 2018b; Gusukuma and Kahhat 2018). In application of the Delphi method, experts are engaged in two or more rounds to respond to questionnaires based on the analytical tool employed (Kauko and Palmroos 2014). The Delphi method has been extensively applied in many studies, but there is no universal guideline for sample sizes for studies (Fernandez-Brana et al. 2019; Veiga et al. 2016). According to Kauko and Palmroos (2014), if the experts considered for a study are homogeneous (i.e., from the same industry), then the number of experts should be between 6 and 12. Hsu and Sandford (2007) conducted a study applying the Delphi method with six expert's opinions to evaluate selection criteria for medical waste disposal. dos Muchangos et al. (2015) employed seven experts' view in analyzing barriers to municipal solid waste. Agyemang et al. (2018) used four experts to evaluate the barriers to green supply chain redesign in cashew production. Giunipero et al. (2012) utilized three experts' view in analyzing barriers to sustainability in supply management. Tarei et al. (2018) also applied six expert views in quantifying supply chain risk in the Indian petroleum industry.

Existing studies applying the Delphi method emphasize the importance of expert's experience, capability, qualification, and knowledge about the criteria under study rather than the

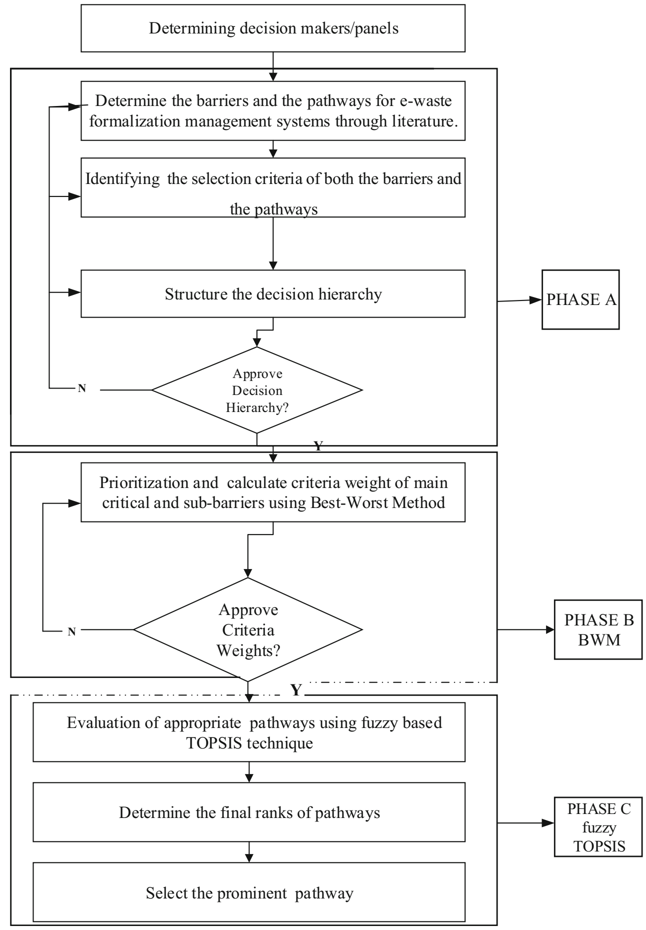

Fig. 1 The research framework of various phases of the techniques applied

sample size (Giannarou and Zervas 2014; Zeh and Christalle 2019). In this study, the Delphi method is employed as applied in previous studies (Bouzon et al. 2016; Islam and Huda 2020b), to assist in identifying the most significant barriers and pathways for the implementation of e-waste formalization management practices.

Best–worst method

The BWM is a powerful and widely employed MCDM technique, which can be used to calculate the weights of the criteria/factors. BWM was developed by Rezaei (2015) and has been extensively and successfully utilized in analyzing various issues in real-world applications including social sustainability (Badri Ahmadi et al. 2017), assessing success factors of technological innovation (Ghaffari et al. 2017), bioethanol facility location selection (Kheybari et al. 2019), evaluating barriers of sustainable manufacturing (Malek and Desai 2019), sustainable circular supplier section (Kannan et al. 2020), energy efficiency (Gupta et al. 2017), prioritization of cloud-based e-learning providers (Pour et al. 2019), sustainable distributed energy systems(Lin et al. 2019), hospital service evaluation (Fei et al. 2020), service quality of airline industry (Gupta 2018a), and logistic performance indicators (Rezaei et al. 2018). Hence, this study selected BWM to analyze the criteria weight of both the critical and sub-barriers over AHP, due to the following reasons: BWM requires fewer pairwise comparisons, due to its vector-based technique; BWM operates in accordance with integers, while AHP combines integers and fractional values; BWM is straightforward and easily understood during computation than AHP; and the BWM technique provides more consistency than AHP, which indicates that BWM offers more reliable and accurate results than AHP (Kheybari et al. 2019; Rezaei 2015). Therefore, here are the steps of the BWM technique applied in this study, as indicated in previous studies (Badri Ahmadi et al. 2017; Rezaei 2015).

Step 1. In this step, the decision-maker determines the criteria. In this study, we have nine critical barriers and thirty-two sub-barriers ($c_1, c_2. \ldots c^n$).

Step 2. Determine the best (B) and worst (W) critical and sub-criteria. In this step, the decision-maker selects the best and the worst criteria among the set of criteria/barriers presented in step 1. The best criteria represent the most important criteria, and the worst criteria denote the least important criteria.

Step 3. Conduct the pairwise comparison between the best criterion and the other criteria. In BWM, usually a 1–9 scale is utilized to compare the two alternatives selected to indicate their relative importance or performance. For adopting sustainable formal e-waste management approach, we use the 1–9 scale to conduct our pairwise comparison as it has proven to be an effective measurement scale to provide qualitative information and also enable unknown weights to be calculated (Rezaei 2015). Here, the decision-makers determine their preference using the scale between 1 and 9 (where 1 is equally important and 9 is extremely more important). The result in the best-to-others (BO) vector would be: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} indicates the preference of the best criterion B over criterion j, and it can be deduced that $a_{BB} = 1$.

Step 4. Determine the preference of all the other criteria over the worst criterion using a number between 1 and 9 (where 1 is equally important and 9 is extremely more important). The result in the others-to-worst (OW) vector would be: $A_w = (a_{1w}, a_{2w}, \cdots, a_{nw})^T$, where a_{jw} indicates the preference of the criterion j over the worst criterion w, and it can be deduced that $a_{ww} = 1$.

Step 5. Find the optimal weights $(w_1{}^*, w_2{}^*, w_3{}^* \ldots\ldots w_n{}^*)$. The optimal weights of criteria will satisfy the following requirements: For each pair of w^B/w^j and w^j/w^w, the ideal situation is where $w^B/w^j = \alpha^{Bj}$ and $w^j/w^w = \alpha_{jw}$. Therefore, in order to be as close as possible to the ideal situation, we should find a solution to the absolute differences $\{|w_B - \alpha_{Bj} w_j|, |w_j - \alpha_{jw} w_w|\}$, for all j is minimized and can be formulated as follows:

$$\begin{aligned} &\min, \max\left\{\left|w_B - \alpha_{Bj} w_j\right|, \left|w_j - \alpha_{jw} w_w\right|\right\} \\ &\text{s.t.} \\ &\sum_j w_j = 1, \quad w_j \geq 0, \quad \text{for all } j \end{aligned} \tag{1}$$

Problem (1) can be transferred to the following linear programming problem:

$$\begin{aligned} &\min \quad \xi^l \\ &\text{s.t.} \\ &\left|w_B - \alpha_{Bj} w_j\right| \leq \xi^l, \text{for all j} \\ &\left|w_j - \alpha_{jw} w_w\right| \leq \xi^l, \text{for all j} \\ &\sum_j w_j = 1, \qquad w_j \geq 0, \quad \textit{for all } j \end{aligned} \tag{2}$$

After solving problem (2), the optimal weights $(w_1{}^*, w_2{}^*, w_3{}^* \ldots\ldots w_n{}^*)$ and ξ^{l*} are obtained. ξ^{l*} can be directly considered as an indicator of the consistency of the comparison system. The closer the value of ξ^{l*} is to zero, the higher the consistency is, and thus, the more reliable the comparisons become (Asante et al. 2019).

Fuzzy TOPSIS technique

In this present study, the proposed pathways are evaluated and ranked using the fuzzy TOPSIS technique. The fuzzy TOPSIS is a MCDM technique for criteria selection and rankings (Hwang and Yoon 1981). The TOPSIS method is commonly employed for various studies involving rankings of factors/criteria on the basis that its evaluation process and computation are straightforward, coherent, and simple to understand (Coban et al. 2018). The TOPSIS technique works such that the best alternative would be the one that is close to the positive ideal solution and extreme from the negative ideal solution (Gupta 2018b; Liu and Wei 2018). Nevertheless, the classic TOPSIS technique is characterized by limitations, including imprecision, vagueness, and subjectivity when using crisp values, which affect the decision-making process under a fuzzy environment. Therefore, to address inherent subjectivity and vagueness, we apply the concept of fuzzy set theory along with fuzzy numbers (Guo and Zhao 2015; Gupta and Barua 2018a; Sirisawat and Kiatcharoenpol 2018). In this present study, we integrate the TOPSIS technique with fuzzy numbers to address imprecision, vagueness, and subjectivity under a fuzzy environment. The fuzzy TOPSIS technique was first proposed by Chen (2000) to resolve MCDM concerns under a fuzzy environment (Sirisawat and Kiatcharoenpol 2018). The fuzzy TOPSIS technique is employed in this study to analyze and rank pathways to enhance effective adoption and implementation of e-waste formalization management practices. The steps of the fuzzy TOPSIS technique is given as follows (Gupta and Barua 2017; Wu et al. 2017):

The introduction of the linguistic evaluation scale and fuzzy numbers for comparison matrix. Here, the fuzzy number applied is defined by the triangular fuzzy numbers (TFN), which describe the linguistic scale of the criteria and pathways. The linguistic scale and fuzzy numbers are presented in (Table 2) (Liu and Wei 2018). The scale was used to set up the comparison matrix (k_{ij}), between the alternatives and the sub-barriers. The linguistic scale of this study is justified based on literature and also maintains the principle that triangular fuzzy numbers lie in the range [0, 1], rejecting the normalization requirement.

After the construction of the comparison matrix table, the next step is to calculate the weighted normalized decision matrix. The weighted, normalized decision matrix is calculated by using the following equation:

$$V = \left[v_{ij}\right]_{m\times n} \text{ where } i = 1, 2, 3, \ldots m, \quad j = 1, 2, 3, \ldots n, \quad \text{and } v_{ij} = k_{ij\otimes wj} \tag{3}$$

The next step is to determine the ideal FPIS and FNIS, where FPIS and FNIS are the fuzzy positive ideal and the fuzzy negative ideal solution, respectively:

$$A^{+} = \left\{v_1^{+}, \cdots\cdots v_n^{+}, \right\}, \text{where } v_j^{+} = \left\{\max\left(v_{ij}\right) \text{ if } j\xi J; \quad \min\left(v_{ij}\right) \text{ if } \quad j\xi J'\right\}, \quad j = 1\cdots n \tag{4}$$

Table 2 Linguistic scale for pathway selection

Linguistic variable	Fuzzy numbers
Low influence (L)	(0.0, 0.2, 0.4)
Medium influence (M)	(0.2, 0.4, 0.6)
High influence (H)	(0.4, 0.6, 0.8)
Very high influence (VH)	(0.6, 0.8, 1.0)
Excellent (E)	(0.8, 1.0, 1.0)

$$A^{-} = \left\{v_1^{-}, \cdots\cdots v_n^{-}, \right\}, \text{ where } v_j^{-} = \left\{\min\left(v_{ij}\right) \text{ if } j\xi J; \quad \max\left(v_{ij}\right) \text{ if } \quad j\xi J'\right\}, \quad j = 1\cdots n \tag{5}$$

Step 1. Next, calculate distance alternatives of FPIS using Eq. (6) and FNIS using Eq. (7) below:

$$d_i^{+} = \left\{\sum_{j=1}^{n}\left(v_{ij}-v_{ij}^{+}\right)^2\right\}^{1/2}, i\cdots\cdots m$$
$$d_i^{-} = \left\{\sum_{j=1}^{n}\left(v_{ij}-v_{ij}^{-}\right)^2\right\}^{1/2}, i\cdots\cdots m \tag{6}$$

Step 2. Next, calculate closeness coefficient (CC_i) of each alternative by using the following equation:

$$CC_i = \frac{d_i^{-}}{d_i^{-} + d_i^{+}} \quad , i = 1\cdots\cdots m, \quad CC_i\varepsilon(0, 1) \tag{7}$$

Step 3. The final step is to rank all the alternatives to select the best alternative based on the (CC_i) values in descending order.

Final selection of criteria for the study

The first step involves a comprehensive examination of the literature review in selecting the criteria for the study. In this case, eleven critical barriers, thirty-two sub-barriers, and fifteen pathways were identified through reviewing prior studies on e-waste management practices. These criteria were then sent to e-waste experts for deliberation to ascertain whether these criteria are significant in addressing e-waste formalization challenges through consensus building. After two different rounds of discussions with experts, the eleven critical barriers were pruned to nine. However, the sub-barriers and pathways presented were maintained. The experts were then asked to categorize all the sub-barriers under the critical barriers to the study. Then, BWM and fuzzy TOPSIS questionnaires were designed for data collection.

Data collection

To obtain data and analyze the barriers and the pathways for the implementation of e-waste formalization management, this study assembled experts with varied expertise in the e-waste industry in Ghana. By considering the steps in the Delphi method application (Giunipero et al. 2012; Gupta and Barua 2016; Kauko and Palmroos 2014), the study purposively sampled six experts with an average experience of each expert being 10 years and over in the e-waste industry. The reason for selecting six experts includes the fact that the Delphi method and the MCDM approach can be used with limited sample size (Bhatia and Srivastava 2018) to ensure consistency and make the results realistic (Tarei et al. 2018), on the basis of experts' experience and knowledge in the industry and their understanding of study objectives (Pun and Hui 2001; Tarei et al. 2018). Furthermore, there have been copious studies published earlier that have used inputs from five or less number of experts for analysis (Agyemang et al. 2018; Antarciuc et al. 2018; Giunipero et al. 2012; Gupta and Barua 2018b; Luthra et al. 2017). The experts for the study were assembled from academia, stakeholders, government, and private institutions such as ministries, development agencies, and international nongovernmental organizations. These experts work in various management positions as regional head, ministry directors, managers, and consultants in their respective organizations. The experts selected for the study were engaged at three separate times by two authors to obtain sufficient data for the study. Firstly, after reviewing relevant literature to identify the significant barriers and pathways to e-waste formalization, the shortlisted criteria were then discussed with the experts for approval and recommendations for addition of new criteria or if any of the shortlisted barriers or pathways be removed from the list. In the second engagement, the final list of the barriers and the pathways with BWM and fuzzy TOPSIS structured questionnaires was sent to the experts for pairwise comparison of the criteria. In the third engagement, the completed questionnaires were sent back to the experts for final verification before computation for the analysis. The data collection lasted for 6 weeks. Due to the time schedules of the experts, four were directly interviewed in a face-to-face interaction, while the other two were interviewed on the phone.

Results

Calculation of criteria weight using the best–worst method

After the final consensus on the selection of criteria for the study by the e-waste management experts, the best and worst preferences were determined. A pairwise comparison matrix of the critical and sub-barriers was constructed using a scale of 1–9 for subsequent calculation of the criteria weights. Table 3 presented above indicates how experts determined the best and worst of the critical barriers, and the remaining pairwise comparison of the sub-barriers is presented in Tables 9, 10, and 11 of the Appendix. The findings of the critical barriers and sub-barriers impeding e-waste formalization management practices are presented in Tables 4 and 5, as well as a graphical presentation of the critical barriers is presented in Fig. 2.

Application of fuzzy TOPSIS to analyze pathways for e-waste formalization

In order to resolve the complexity of e-waste management, ranking of applicable pathways has been carried out in many studies to enhance the systematic approach of eliminating informal e-waste management practices. Therefore, identified pathways are ranked based on their final weight values in descending order (Asante et al. 2019; Gupta 2018b). As posited in previous studies, we applied the fuzzy TOPSIS technique to rank pathways

Table 3 Comparison of critical barriers by experts

Best–to-others	BM_1	TB_2	EFL_3	$LELR_4$	$LFEWCP_5$	$LPEW_6$	$LEEP_7$	$LAIF_8$	EPR_9
Lack of appropriate infrastructure ($LAIF_8$)	3	9	4	6	5	3	5	1	8
Worst-to-others	Worst criteria: transboundary treaties								
BM_1		3							
TB_2		1							
EFL_3		5							
$LELR_4$		5							
$LFEWCP_5$		2							
$LPEW_6$		4							
$LEEP_7$		7							
$LAIF_8$		9							
EPR_9		2							

Table 4 Results and ranking of criteria barriers

Critical barriers	Criteria weight index	Consistency ratio	Ranking
BM_1	0.1038	0.094	5
TB_2	0.1795	0.094	2
EFL_3	0.2218	0.094	1
$LELR_4$	0.1460	0.094	3
$LFEWCP_5$	0.1012	0.094	6
$LPEW_6$	0.0603	0.094	8
$LEEP_7$	0.0606	0.094	7
$LAIF_8$	0.1257	0.094	4
EPR_9	0.0426	0.094	9

obtained through the Delphi method and literature review. E-waste experts were asked to evaluate all the sub-barriers against the pathways employing the linguistic variables presented in Table 2. The obtained comparison matrix is presented in Table 12 of the Appendix.

Here, after obtaining the comparison matrix, we normalized the fuzzy matrix table using Eq. (3). Next, FPIS A^+ and FNIS A^- were determined using Eqs. (4) and (5). The FPIS and FNIS can be described in this case as $v_1^+ = (1, 1, 1)$, $v_1^- = (0, 0, 0)$. The benefit criteria are denoted in this study as $v_1^- = (0, 0, 0)$ and the cost criteria as $v_1^+ = (1, 1, 1)$. In this study, all the criteria are considered as cost in order to surmount barriers to e-waste formalization leading to the calculation of FPIS and FNIS values. In order to rank the pathways, the closeness coefficient value (CC_i) is obtained by using Eqs. (6) and (7). The first-ranked pathways are (P_{11}) "setting up resourced environmental government agencies for effective monitoring and auditing at the regional levels for appropriate e-waste management practices" and the last ranked pathway is effective and efficient public awareness creation toward e-waste formalization practices (A_7). Hence, the rankings of the pathways are as follows: $P_{11} > P_{15} > P_8 > P_9 > P_4 > P_{14} > P_{12} > P_5 > P_{10} > P_1 > P_3 > P_{13} > P_2 > P_6$ and A_7 in descending order of their weights values. The obtained results were validated by comparing it with other similar methods to verify whether the rankings position were accurate and consistent, as presented in Table 6.

Comparing of pathway results with similar methods

To further determine the validity of the results and rankings of the pathways, we compared our method with two other previous methods: intuitionistic fuzzy VIKOR by Haji Vahabzadeh et al. (2015) and possibilistic TOPSIS theory by Ye and Li (2014), which deal with fuzzy numbers. After validating our results and rankings with two similar methods, there was no indication of significant variation in results and the rankings, as shown in Table 6.

Discussion, sensitivity analysis, and implications

Discussion

With increasing environmental awareness, sustainable e-waste management has become a complex and difficult task for decision-makers. E-waste formalization systems implementation is gaining popularity as the best substitute for informal e-waste management practices. In this study, with the undergird of the best–worst method and fuzzy TOPSIS techniques, the analysis and the rankings of the barriers and the pathways to e-waste formalization management were made simple and understandable by the decision-makers. Nonetheless, acknowledging the complexity of filling the BWM and the fuzzy TOPSIS structured questionnaires, extensive education and guidelines were provided to aid the experts avoid incorrect ratings to prevent inconsistency and unreliability of the study findings. In view of this, the authors had an in-depth grasp of the methods employed and ensured the questionnaires were accurately filled by the experts for further analysis. In this study, the global weights of the sub-barriers were obtained by multiplying the weights of individual critical weights with each local weight of the sub-barriers, as shown in Table 5. The results of the critical barriers are presented in Table 4 and Fig. 2. The findings revealed that economic and financial limitations with a criteria weight index of (0.221) were the most significant barriers impeding the adoption and implementation of formal e-waste management practices. The economic and financial limitation barrier comprises of capital investment to enhance smooth commencement of formal e-waste management systems implementation (Islam and Huda 2020a). This critical barrier has five sub-barriers that are ranked based on their global weights in descending order as follows: $EFLSB_4 > EFLSB_2 > EFLSB_1 > EFLSB_3 > EFLSb_5$ as indicated in Table 5. The second ranked critical barrier is the lack of international trade treaty's implementation (transboundary), with a criteria weight value of (0.179). The implementation of international trade treaties restricting the shipment of e-waste products is key to addressing e-waste formalization in emerging economies (Wang et al. 2016); hence, this barrier needs to be addressed in the short run. This confirms a previous study by Orlins and Guan (2016), who indicated that effective monitoring and workable policies must be formulated to control the incessant shipment of e-waste products from the developed countries to lower- and middle-income countries. The following are the rankings of the sub-barriers: $TBSB_2 > TBSB_3 > TBSB_1 > TBSB_4$.

The lack of environmental laws and regulations with a criteria weight of (0.146) was ranked third most critical barrier

Table 5 Results and ranking of sub-barriers for e-waste formalization

Critical barriers	MC weights	Consistency ratio	Sub-barriers	Local weight	Consistency ratio	Global weights	Rank
BM_1	0.1038	0.0940	$BMSB_1$	0.2315	0.2851	0.0240	18
BM_1	0.1038	0.0940	$BMSB_2$	0.3018	1.2851	0.0313	15
TB_2	0.1795	0.0940	$TBSB_1$	0.2459	0.1994	0.0441	6
TB_2	0.1795	0.0940	$TBSB_2$	0.2921	0.1994	0.0524	3
TB_2	0.1795	0.0940	$TBSB_3$	0.2607	0.1994	0.0467	5
TB_2	0.1795	0.0940	$TBSB_4$	0.2013	0.1994	0.0361	10
EFL_3	0.2218	0.0940	$EFLSB_1$	0.1848	0.2526	0.0409	7
EFL_3	0.2218	0.0940	$EFLSB_2$	0.2229	0.2526	0.0494	4
EFL_3	0.2218	0.0940	$EFLSB_3$	0.1788	0.2526	0.0396	8
EFL_3	0.2218	0.0940	$EFLSB_4$	0.2539	0.2526	0.0563	2
EFL_3	0.2218	0.0940	$EFLSB_5$	0.1596	0.2526	0.0352	13
$LELR_4$	0.1460	0.0940	$LELRSB_1$	0.4350	0.2033	0.0635	1
$LELR_4$	0.1460	0.0940	$LELRSB_2$	0.1677	0.2033	0.0244	17
$LELR_4$	0.1460	0.0940	$LELRSB_3$	0.1551	0.2033	0.0226	20
$LELR_4$	0.1460	0.0940	$LELRSB_4$	0.2423	0.2033	0.0353	12
$LFEWCP_5$	0.1012	0.0940	$LFEWCPSB_1$	0.2298	0.1990	0.0232	19
$LFEWCP_5$	0.1012	0.0940	$LFEWCPSB_2$	0.1998	0.1990	0.0202	24
$LFEWCP_5$	0.1012	0.0940	$LFEWCPSB_3$	0.3570	0.1990	0.0361	11
$LFEWCP_5$	0.1012	0.0940	$LFEWCPSB_4$	0.2134	0.1990	0.0216	22
$LPEW_6$	0.0603	0.0940	$LPEWSB_1$	0.3701	0.1324	0.0223	21
$LPEW_6$	0.0603	0.0940	$LPEWSB_2$	0.1702	0.1324	0.0103	34
$LPEW_6$	0.0603	0.0940	$LPEWSB_3$	0.2355	0.1324	0.0142	28
$LPEW_6$	0.0603	0.0940	$LPEWSB_4$	0.2243	0.1324	0.0135	30
$LEEP_7$	0.0606	0.0940	$LEEPSB_1$	0.2475	0.2518	0.0141	29
$LEEP_7$	0.0606	0.0940	$LEEPSB_2$	0.3232	0.2518	0.0196	25
$LEEP_7$	0.0606	0.0940	$LEEPSB_3$	0.1778	0.2518	0.0108	33
$LEEP_7$	0.0606	0.0940	$LEEPSB_4$	0.2515	0.2518	0.0152	27
$LAIF_8$	0.1257	0.0940	$LAIFSB_1$	0.2496	0.1271	0.0314	14
$LAIF_8$	0.1257	0.0940	$LAIFSB_2$	0.2360	0.1271	0.0210	23
$LAIF_8$	0.1257	0.0940	$LAIFSB_3$	0.3036	0.1271	0.0381	10
$LAIF_8$	0.1257	0.0940	$LAIFSB_4$	0.2108	0.1271	0.0265	16
EPR_9	0.0426	0.0940	$EPRSB_1$	0.3940	0.2591	0.0168	26
EPR_9	0.0426	0.0940	$EPRSB_2$	0.2951	0.2591	0.0126	32
EPR_9	0.0426	0.0940	$EPRSB_3$	0.3109	0.2591	0.0132	31

obstructing e-waste formalization implementation in the Ghanaian context. The existence of environmental laws and regulations drive organizations and individuals to comply by adopting legal methods of operating to promote environmental improvement. This barrier requires short run attention to facilitate the implementation of formal approach of managing e-waste. Agyemang et al. (2018) argued that organizations face difficulties in implementing required measures in managing the redesign of products for environmental concerns due to lack of roadmap to serve as a guideline. Again, Mahpour (2018) argued that policy makers' inability to formulate and implement laws in addressing waste management concerns discourages the adoption of innovative practices to protect the environment. The rankings of the sub-barriers are follows: $LELRSB_1 > LELRSB_4 > LELRSB_2 > LELRSB_4$.

The lack of appropriate infrastructure with a criteria weight of (0.1257) was ranked as the fourth critical barrier hindering formalization practices of e-waste in Ghana. The barrier needs to be addressed in the short term, but efforts must be made to address it in the long run. Awasthi et al. (2018) mentioned that, without appropriate infrastructure, e-waste operators/organizations cannot pursue the path of adopting the standard method of managing e-waste and implement appropriate practices in the e-waste sector. The ranking of the sub-barriers under this barrier are as follows: $LAIFSB_3 > LAIFSB_1 > LAIFSB_4 > LAIFSB_2$.

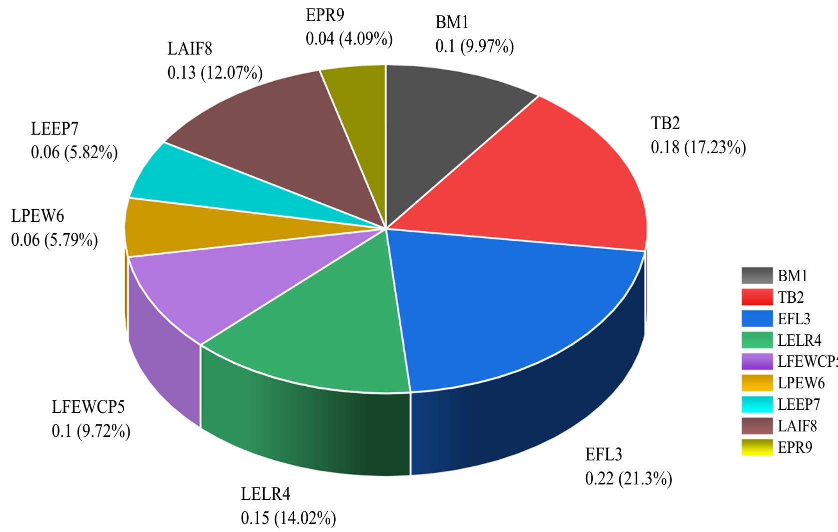

Fig. 2 Graphical presentation of critical barriers

The barrier related to media participation in environmental awareness advocacy with a criteria weight of (0.103) is the fifth-ranked critical barrier and must be addressed in the short run. The role of media championing against the informal recycling of e-waste in Ghana is insignificant compared with their advocacy against small-scale mining (Oteng-Ababio 2010). In this instance, organizations, such as NGOs, can collaborate with the media and other agencies to create awareness of environmental and social consequences of informal e-waste management (Kumar and Dixit 2018a). The following are the sub-barriers under this major barrier: $BMSB_1 > BMSB_2$.

The lack of formal e-waste collection points/centers with a criteria weight of (0.101) was ranked as the sixth critical barrier. This barrier requires a medium-term solution. The results indicate that the lack of formal e-waste collection centers propels households to resort to and engage with informal e-waste collectors who are mobile and easy access to the communities (Rajesh Ejiogu 2013). In order to overcome this barrier, it is necessary to establish authorized e-waste collection centers to encourage households from engaging with informal scavengers (Sirisawat and Kiatcharoenpol 2018). The sub-barriers are ranked as $LFWPSB_1 > LFWPSB_3 > LFWPSB_4 > LFWPSB_2$.

The seventh-ranked most critical barrier is the lack of external environmental entities' contribution in creating awareness about informal methods of managing waste. It has a criteria weight of (0.060) and must be addressed in the long term. These are the sub-barriers rankings: $EEPSB_2 > EEPSC_4$

Table 6 Comparison of results and ranking with other methods

Pathways	Fuzzy TOPSIS		Possibilistic TOPSIS theory		Fuzzy VIKOR	
	CC_i	Ranking	CC_i	Ranking	CC_i	Ranking
P_1	0.9885	10	0.7812	8	0.3962	7
P_2	0.9875	13	0.6367	12	0.3108	10
P_3	0.9879	11	0.7208	11	0.2538	14
P_4	0.9894	5	0.8093	6	0.1980	12
P_5	0.9889	8	0.7138	13	0.3055	11
P_6	0.9874	14	0.7293	9	0.3812	8
P_7	0.9862	15	0.7962	7	0.4098	5
P_8	0.9910	3	0.8176	3	0.5172	4
P_9	0.9894	4	0.8172	4	0.5176	3
P_{10}	0.9886	9	0.6044	15	0.2367	13
P_{11}	0.9920	1	0.8808	1	0.6808	1
P_{12}	0.9892	7	0.7255	10	0.3293	9
P_{13}	0.9877	12	0.6280	14	0.1704	15
P_{14}	0.9892	6	0.8098	5	0.4093	6
P_{15}	0.9912	2	0.8414	2	0.5814	2

> $EEPSB_1$ > $EEPSB_3$. The activities of informal e-waste recyclers have become a global concern, which has stimulated development agencies and industry players to champion the need to adopt a formalization system being practiced in developing countries to safeguard the environment and the spread of disease (Tong et al. 2018).

The lack of public understanding of informal e-waste management is the eighth-ranked barrier. The criteria has a weight of 0.094. The literature establishes that there is no clear-cut understanding between informal and formal methods of managing e-waste, making households more vulnerable in contributing to the former (Aparcana 2017). The rankings of the sub-barriers are $LPEWSB_1$ > $LPEWSB_3$ > $LPEWSB_4$ > $LPEWSB_2$. The less significant critical barrier is the lack of extended producer responsibility with a criteria weight of (0.042). In this situation, producers fail to assume responsibility by taking back the end of life (EOL) products from consumers, which subsequently ends up being managed informally causing environmental challenges (Zeng et al. 2017). The following are the rankings of the sub-barriers: $EPRSB_1$ > $EPRSB_3$ > $EPRSB_2$.

Similarly, Table 6 highlights and ranks all the fifteen proposed pathways to the adoption and implementation of a formal approach of managing e-waste. Among the fifteen pathways, "setting up resourced environmental government agencies for effective monitoring and auditing at the regional levels for appropriate e-waste management practices (P_{11})" with a (CC_i) value of (0.9919) was ranked first. Fujimori et al. (2016) indicated that agencies discharge their duties effectively when necessary materials are available, which is essential in the implementation of related practices in addressing e-waste management challenges through coercive, mimetic, and normative means. Provision of tax cuts, incentives, and technical assistance to enable informal e-waste recyclers to adopt a formal management system (P_{15}) was ranked second with a CC_i value of (0.991170). Earlier studies have enunciated the significance of tax exemptions and incentives as a way of enhancing organizations applying modern methods and technologies in recycling e-waste (Zhang and Xu 2016). The remaining pathways are ranked based on their (CC_i) values: $P_8 > P_9 > P_4 > P_{14} > P_{12} > P_5 > P_{10} > P_1 > P_3 > P_{13} > P_2 > P_6$ and P_7.

Sensitivity analysis

Sensitivity analysis (SA) is a very useful and powerful tool to test the relative importance of the model and to eliminate any inherent bias. Sensitivity analysis can be conducted in multiple ways, such as varying the weights assigned to a criterion, replacing initial weights with different weights, or altering the weights assigned to a particular expert. It is usually conducted to check the robustness and validate the authenticity of the proposed framework to address any possible bias that characterizes human decision-making (Gupta and Barua 2018b). Therefore, in this study, a sensitivity analysis was conducted by varying the weight of the first-ranked barrier and the pathways as applied in previous studies (Prakash and Barua 2016). Hence, in this instance, the weight of ($EFL_3 = 0.223$) and ($P_{11} = 0.9862$) were varied from 0.1 to 0.9, and the process was repeated across the remaining barriers and the pathways are presented in Tables 7 and 8 with pictorial evidence from Figs. 3, 4, and 5.

In this study, since any variation in the results of critical barriers may affect the global weights of the sub-barriers, a similar sensitivity analysis was run throughout the sub-barriers by varying the highest global weight ($LELRSB_1 = 0.6535$), from 0.1 to 0.9 presented in Fig. 3. In order to address inaccuracies and inconsistencies in the final ranking and neutralize any human influence during the decision-making process, conducting sensitivity analysis varying the highest weights and run from 0.1 to 0.9 is widely recognized as an appropriate approach, since it helps in checking variations in the final ranking (Gupta 2018b; Kumar and Dixit 2019). Therefore, the outcome of the sensitivity analysis carried out on critical barriers, sub-barriers, and pathways had significant changes, and the model employed is unbiased and robust.

Theoretical contribution

One major theoretical contribution of this study to literature is the proposition of a novel approach of a three-phase methodology (Delphi method, BWM, and fuzzy TOPSIS techniques) to identify and evaluate barriers and pathways for e-waste formalization management implementation. Additionally, it gives in-depth insight into model application procedures in an integrated manner, particularly multiplicity models for ratings to solve specific problems.

The findings of the study, which resonate with existing literature, contribute to the evidence that comparison of results with other studies is often challenging due to variations in methodological approach, set of criteria, and policy direction (Garlapati 2016; Kumar and Dixit 2018a; Milovantseva and Fitzpatrick 2015; Wang et al. 2017). It is imperative to state that many studies such as Masud et al. (2019) and Xu et al. (2020) highlighting barriers to sustainable e-waste management in developing countries are similar to our study. For instance, Wang et al. (2017) underscored the lack of financial constraints as a key barrier impeding e-waste recycling in China, and this assertion clearly resonates with our findings as a key barrier in the Ghanaian context. In the study of Bhatia and Srivastava (2018), they indicated that the lack of economic incentives and tax preference and imperfect legal system and channels to collect used e-waste products are the key barriers that significantly impede sustainable e-waste management in India. Similarly, in this present study, the lack of environmental laws and regulations ($LELR_4$) and the lack of formal e-waste collection points/centers ($LFEWCP_5$) are

Table 7 SA of critical barriers after varying criteria weight value of (EFL_3) from 0.1 to 0.9

Critical barriers	Normalized values	Run 1 (0.1)	Run 2 (0.2)	Run 3 (0.3)	Run 4 (0.4)	Run 5 (0.5)	Run 6 (0.6)	Run 7 (0.7)	Run 8 (0.8)	Run 9 (0.9)
EFL_3	0.223	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
BM_1	0.103	0.093	0.083	0.073	0.063	0.053	0.043	0.033	0.023	0.013
TB_2	0.179	0.206	0.196	0.186	0.176	0.167	0.156	0.146	0.136	0.126
$LELR_4$	0.146	0.184	0.174	0.164	0.154	0.144	0.134	0.124	0.104	0.094
$LFEWCP_5$	0.126	0.142	0.133	0.124	0.115	0.106	0.097	0.088	0.079	0.070
$LPEW_6$	0.104	0.136	0.126	0.116	0.106	0.096	0.086	0.076	0.066	0.056
$LEEP_7$	0.101	0.121	0.11	0.099	0.088	0.077	0.066	0.055	0.044	0.033
$LAIF_8$	0.061	0.089	0.08	0.071	0.062	0.053	0.044	0.035	0.026	0.017
EPR_9	0.060	0.070	0.063	0.054	0.045	0.036	0.027	0.018	0.009	0.000
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

identified as critical barriers for e-waste formalization management.

Furthermore, several existing studies (Bhatia and Srivastava 2018; Lu et al. 2014; Oteng-Ababio et al. 2020; Simms et al. 2020) proposed solutions resonating with the applicable pathways essential for the implementation of e-waste formalization management as suggested in the present study. A previous study by Zhao and Yang (2018) highlighted the importance of incorporating private organizations in policy formulation related to e-waste management, resourcing government agencies for effective monitoring and education, provision of tax stimulus packages, provision of training programs to equip e-waste recyclers with new technology, and tool application to enhance the adoption and implementation of formal e-waste management.

Policy and practical implications of the study

The findings of the study have the potential to inform policy makers and practitioners on the implementation of e-waste formalization management practices in Ghana and other developing countries. After analyzing the relationship among the barriers and the pathways to e-waste formalization management practices, it is observed that the applied framework is robust. Its underpinnings provide better amplification of the criteria considered for the study. The outcome of the study indicated that the barriers are interconnected; therefore, it requires absolute commitment from the government, industry actors, and major stakeholders, including managers, consumers, and recyclers, to address these concerns. Financial and economic constraints were ranked first among all the barriers in the implementation of e-waste

Table 8 Ranking of pathways in sensitivity analysis when weight of (P_{11}) was run 0.1–0.9

Pathways	Normalized	Run 1 (0.1)	Run 2 (0.2)	Run 3 (0.3)	Run 4 (0.4)	Run 5 (0.5)	Run 6 (0.6)	Run 7 (0.7)	Run 8 (0.8)	Run 9 (0.9)
P_1	10	8	11	11	9	10	10	10	9	10
P_2	13	13	14	12	15	13	12	11	13	11
P_3	11	11	10	9	13	11	11	12	11	13
P_4	5	4	6	6	6	5	4	4	3	5
P_5	8	7	9	8	10	8	7	8	7	8
P_6	14	12	12	15	12	12	14	13	14	14
P_7	15	15	15	14	14	15	13	14	15	15
P_8	3	3	4	5	2	3	2	3	5	3
P_9	4	5	2	4	3	4	5	4	4	4
P_{10}	7	7	8	7	8	9	9	7	9	9
P_{11}	1	1	1	1	1	1	1	1	1	1
P_{12}	9	7	5	5	7	7	6	6	6	7
P_{13}	2	14	13	13	11	14	12	15	10	12
P_{14}	6	5	7	6	5	6	6	6	8	6
P_{15}	3	2	3	2	4	2	3	2	2	2

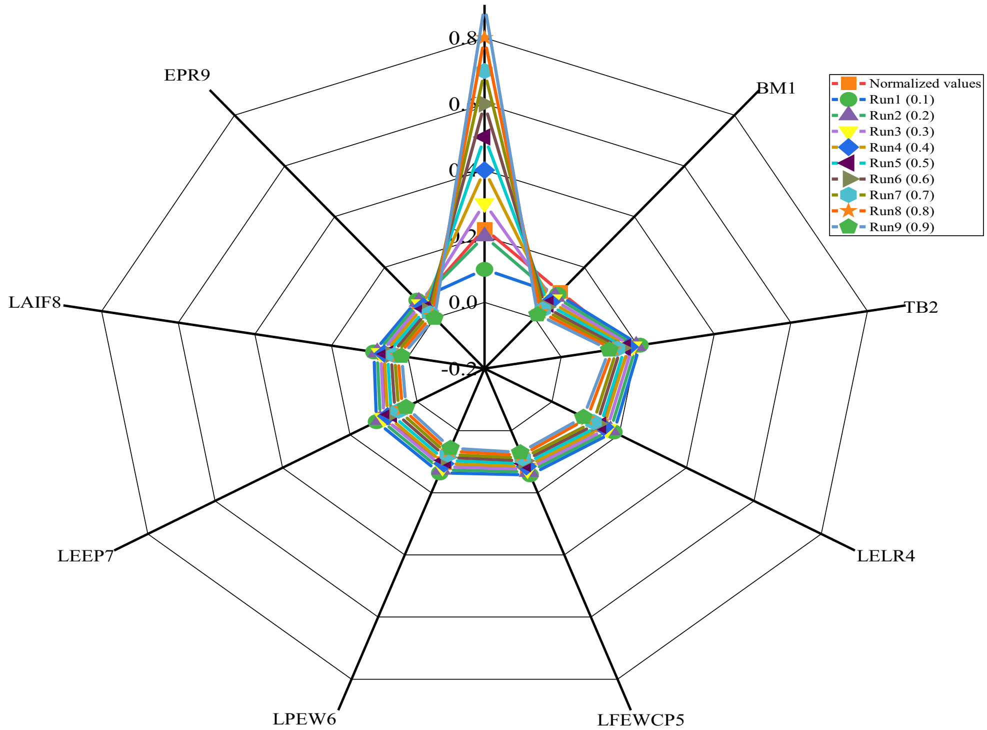

Fig. 3 Results of sensitivity analysis of the critical barriers

formalization practices in Ghana. Therefore, the government should allocate financial resources to cushion e-waste entrepreneurs at the initial stage of integrating formalization management practices to stimulate a greater proportion of informal e-waste entrepreneurs and operators to implement formal e-waste management systems. According to Ikhlayel (2018), establishing appropriate and sustainable e-waste management is capital intensive for installation of new facilities, training, technology, and transportation, particularly in the initial stage. The services of external entities such as the media and environmental protection agencies are critical. Therefore, governments should collaborate and involve these agencies in policy development. In Ghana,

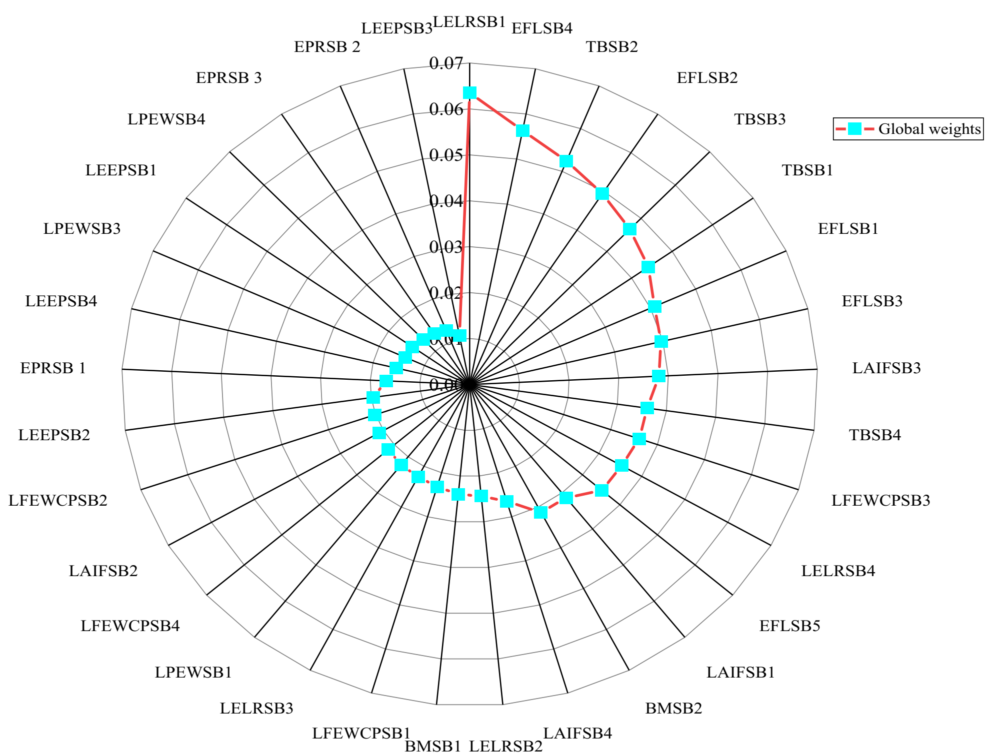

Fig. 4 Results of sensitivity analysis of sub-barriers

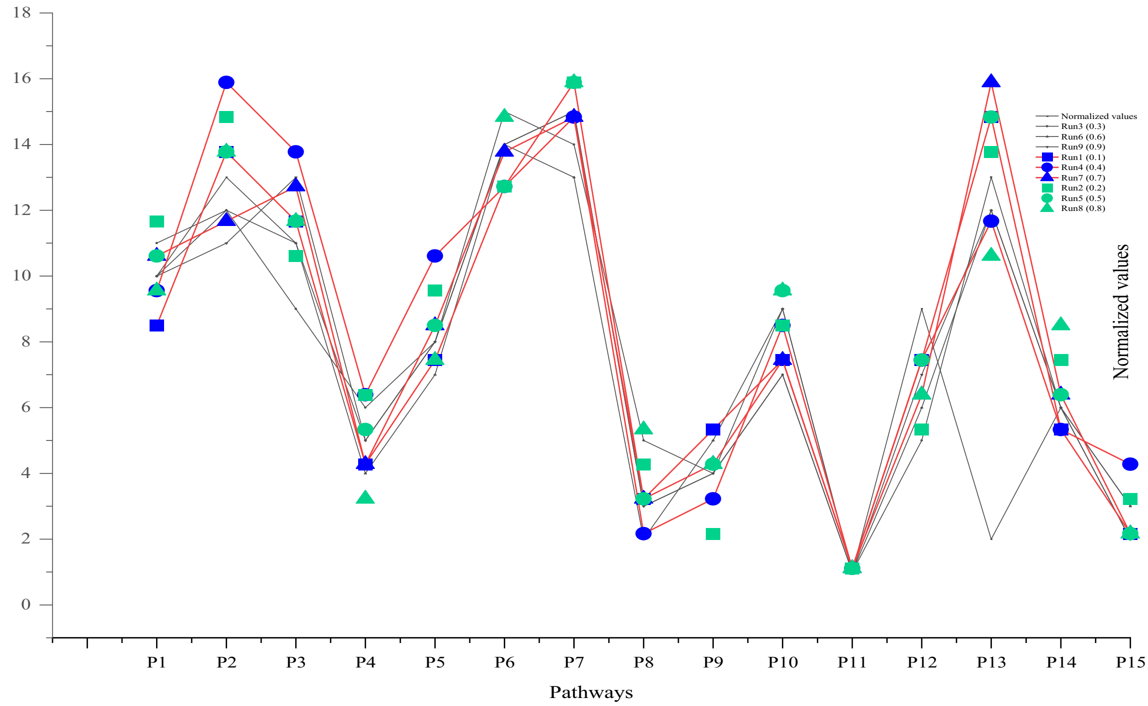

Fig. 5 Outcome of sensitivity analysis pathways

developmental agencies and NGOs including the Global Alliance for Health and Pollution (GAHP), the United Nations Industrial Development Organization (UNIDO), and Green Advocacy Ghana (Green Ad) should team up with universities and other civil society groups to embark community workshops, seminars, and training programs to enlighten the consumers about the impact of informal e-waste management practice on human lives and the environment. Also, such broader engagement can aid in ameliorating consumers' understanding of e-waste recycling and reuse.

According to the evaluators, the lower level of awareness about informal e-waste management was predominant among the less educated populace in lower-income communities. As such, policy makers need to increase public awareness in such communities through intensive campaigns. It is essential for developing countries to implement advanced e-waste management measures such as consumer's participation and return of obsolete e-waste product for new product with little cost (zero waste), innovations that are being implemented in many developed economies. According to Oguri et al. (2018), practicing deposit refund system implementation helps consumers to actively participate in zero e-waste management through reimbursement of their fund deposited when an already purchased electronic product becomes obsolete and returned to the manufacturers. This incentive plan helps in dissuading consumers from auctioning their unwanted electronic products to informal recyclers. According to the evaluators, the lack of e-waste collection stations is a critical concern that obstructs the implementation of e-waste formalization management. Established collection centers have a great potential to enhance easy e-waste collection and disposal. Also, the findings of the study provide comprehensive insights for DMs, stakeholders, and industry actors in developing and emerging economies to enact and enforce compliance of new and existing policies and conventions forbidding the shipment of e-waste from the developed economies. Additionally, owing to the noxious content in e-waste, observance of environmental rules and regulations is needed and must strictly be enforced and complied by the e-waste entrepreneurs and operators.

Finally, as earlier indicated, the relative importance of each of the barriers and the pathways is determined through experts' decision. The proposed novel methodological approach of the study can support DMs to enhance decision evaluation of formal e-waste management. Although the study is focused on Ghana within a global perspective, our findings shed light on other jurisdiction and countries that face similar barriers to the implementation of e-waste formalization management.

Conclusions

Due to the impact of informal e-waste management practices on human lives, the environment, the society, and the economy, there has been evolving pressure on the implementation of e-waste formalization management to recover e-waste components, particularly in developing countries. E-waste formalization practices bring an opportunity for the e-waste industry to address environmental sustainability and health risk concerns as well as creating business opportunities. However, barriers to e-waste formalization management implementation exist in most developing countries. Guided by three research objectives, this study evaluates critical barriers and applicable pathways for e-waste formalization management in Ghana's e-waste sector through a hybrid methodology. The implementation of sustainable e-waste management is a complex task. Through extensive literature review and the use of the Delphi method, nine critical barriers, thirty-four sub-barriers, and fifteen pathways were identified and evaluated by six experts. Three separate engagements with the experts were carried out to evaluate pairwise ratings of the criteria, by completing BWM and fuzzy TOPSIS structured questionnaires. Subsequently, the barriers and the pathways identified are analyzed and ranked by employing the BWM and fuzzy TOPSIS model, respectively.

The barriers and pathways were ranked based on the criteria weights to enable policy makers avoid discrepancies and expedite the decision-making process to enhance systematic integration of e-waste formalization management. From the findings, barriers that affect the implementation of e-waste formalization management are quite complex and hierarchical and such requires urgent attention. The findings show that economic and financial limitations (EFL_3), international trade treaties (transboundary) (TB_2), lack of environmental laws and regulations ($LELR_4$), and lack of appropriate infrastructure ($LAIF_8$) are the major key barriers; hence, more effort should be directed at eliminating these barriers for successful implementation of e-waste management in the Ghanaian context. Again, from the study, setting up resourced government agencies for effective monitoring and auditing environmental practices at the regional levels for an e-waste formalization was ranked as the first pathway to be implemented within the short term. Sensitivity analysis was conducted to verify the robustness of the techniques and address any bias. The results obtained deduce that the techniques applied for the study are well fitting and provide decision support to policy makers and environmental management professionals in drawing strategic initiatives essential for the implementation of formalization management in Ghana.

Important lessons from the study include the fact that developing countries such as Ghana can replicate initiatives implemented by developed countries by authorizing manufacturers to design eco-friendly products and be involved in the collection of e-waste equipment through extended r. Secondly, the enforcement and implementation of appropriate international legislation and conventions on the illegal shipment of e-waste products should be adhered to. Thirdly, environmental and media practitioners should collaborate and create awareness to strengthen consumer knowledge base about e-waste management as an integral area in a product life cycle. Moreover, intensive education and campaigns at the district assembly levels, schools, and markets to enlighten students, consumers, and informal operators about health repercussion associated with illegal e-waste management practices should be encouraged. Furthermore, there should be frequent monitoring and assessment of e-waste management practices by government agencies at the regional and national level to strengthen and ensure effective environmental and health guidelines. We suggest that "The Hazardous and Electronic Waste Control and Management Act 2016" (Act 917) and other management regulations (example LI 2250) outdoored in 2016 in Ghana to address e-waste management menace should be implemented and enforced.

Limitations and future research direction

Despite significant insight about the barriers and pathways to e-waste formalization management, the study still has limitations which can be extended in various ways in future studies. First, this study does not explain the impact of each of the barriers and pathways. Future studies can focus on shedding light on the impact of each barrier. Secondly, understanding the correlation mechanism in the barriers and pathways was not considered, and further studies can explore this problem. From the methodological (Delphi method, BWM, and fuzzy TOPSIS) aspect, six experts were engaged in the evaluation and data collection for the study. Future studies can focus on expanding sample size and the numbers of sections in engagement with experts. Finally, the present study employed the BWM and fuzzy TOPSIS to evaluate barriers and pathways, and future studies can explore more barriers and pathways with the aid of other methods such as the VIKOR method, structural equation modeling (SEM), and fuzzy ELECTRE.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 9 Pairwise comparison of sub-barriers of barrier related to media participation in environmental awareness

Best-to-others	$BMSB_1$	$BMSB_2$
Best criteria: $BMSB_1$	1	5
Worst-to-others	Worst criteria: $MBSB_1$	
$BMSB_1$	4	
$BMSB_2$	1	

Table 10 Pairwise comparison of sub-barriers of economic and financial limitations

Best-to-others	$EFLSB_1$	$EFLSB_2$	$EFLSB_3$	$EFLSB_4$	$EFLSB_5$
Best criteria: $EFLC_4$	1	3	7	5	9
Worst-to-others		Worst criteria: $EFLSC_5$			
$EFLSB_1$		6			
$EFLSB_2$		4			
$EFLSB_3$		3			
$EFLSB_4$		8			
$EFLSB_5$		1			

Table 11 Pairwise comparison of sub-barriers of international trade treaties (transboundary)

BO	$TBSB_1$	$TBSB_2$	$TBSB_3$	$TBSB_4$
Best criterion: $FECC_2$	4	1	3	5
OW	Worst criterion: TBC_4			
$TBSB_1$	4			
$TBSB_2$	6			
$TBSB_3$	3			
$TBSB_4$	1			

Table 12 Fuzzy comparison matrix for pathways

Pathways	$BMSB_1$	$BMSB_2$	$TBSB_1$	$TBSB_2$	$TBSB_3$	$TBSB_4$	$EFLSB_1$	$EFLSB_2$	$EFLSB_3$	$EFLSB_4$	$LELRSB_1$
P_1	0, 0, 0.2	0.6, 0.8, 1	0.2, 0.4, 0.6	0, 0.2, 0.4	0, 0, 0.2	0, 0.2, 0.4	0.6, 0.8, 1	0, 0, 0.2	0.6, 0.8, 1	0, 0, 0.2	0.6, 0.8, 1
P_2	0.6, 0.8, 1	0, 0, 0.2	0, 0.2, 0.4	0.4, 0.6, 0.8	0, 0, 0.2	0.2, 0.4, 0.6	0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0.8, 1, 1	0, 0.2, 0.4
P_3	0, 0.2, 0.4	0, 0, 0.2	0.6, 0.8, 1	0, 0.2, 0.4	0.6, 0.8, 1	0.8, 1, 1	0, 0, 0.2	0, 0.2, 0.4	0.8, 1, 1	0.4, 0.6, 0.8	0.8, 1, 1
P_4	0.8, 1, 1	0.2, 0.4, 0.6	0.8, 1, 1	0.6, 0.8, 1	0.4, 0.6, 0.8	0, 0, 0.2	0.4, 0.6, 0.8	0, 0, 0.2	0, 0.2, 0.4	0.2, 0.4, 0.6	0, 0, 0.2
P_5	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.8, 1, 1	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.8, 1, 1	0.2, 0.4, 0.6	0.8, 1, 1	0.6, 0.8, 1	0.6, 0.8, 1	0.4, 0.6, 0.8
P_6	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0.2, 0.4	0.2, 0.4, 0.6	0.8, 1, 1	0.4, 0.6, 0.8	0.8, 1, 1	0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0, 0.2
P_7	0.2, 0.4, 0.6	0, 0.2, 0.4	0.2, 0.4, 0.6	0.6, 0.8, 1	0, 0, 0.2	0, 0.2, 0.4	0, 0.2, 0.4	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0, 0.2
P_8	0.8, 1, 1	0.8, 1, 1	0, 0.2, 0.4	0.6, 0.8, 1	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1	0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0, 0.2, 0.4
P_9	0.4, 0.6, 0.8	0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0.8, 1, 1	0, 0, 0.2	0, 0, 0.2	0, 0, 0.2	0.6, 0.8, 1	0.8, 1, 1	0.4, 0.6, 0.8
P_{10}	0, 0, 0.2	0.4, 0.6, 0.8	0, 0, 0.2	0, 0, 0.2	0.4, 0.6, 0.8	0, 0, 0.2	0.2, 0.4, 0.6	0.6, 0.8, 1	0.8, 1, 1	0, 0, 0.2	0.2, 0.4, 0.6
P_{11}	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0.8, 1, 1	0.2, 0.4, 0.6	0, 0, 0.2	0, 0.2, 0.4	0, 0, 0.2	0, 0, 0.2	0, 0, 0.2	0.4, 0.6, 0.8	0.8, 1, 1
P_{12}	0.6, 0.8, 1	0, 0, 0.2	0.8, 1, 1	0.4, 0.6, 0.8	0.6, 0.8, 1	0.4, 0.6, 0.8	0, 0, 0.2	0.4, 0.6, 0.8	0.8, 1, 1	0.8, 1, 1	0.6, 0.8, 1
P_{13}	0, 0, 0.2	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0, 0.2	0.8, 1, 1	0.6, 0.8, 1	0, 0, 0.2	0.8, 1, 1	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0, 0, 0.2
p_{14}	0.2, 0.4, 0.6	0.6, 0.8, 1	0.6, 0.8, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.6, 0.8, 1	0.6, 0.8, 1	0.6, 0.8, 1	0.8, 1, 1	0.6, 0.8, 1	0, 0.2, 0.4
P_{15}	0.8, 1, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.8, 1, 1	0, 0, 0.2	0.2, 0.4, 0.6	0, 0, 0.2	0.8, 1, 1	0.8, 1, 1	0, 0, 0.2	0.8, 1, 1

Table 12 (continued)

Pathways	BMSB$_1$	BMSB$_2$	TBSB$_1$	TBSB$_2$	TBSB$_3$	TBSB$_4$	EFLSB$_1$	EFLSB$_2$	EFLSB$_3$	EFLSB$_4$	LELRSB$_1$
LELRSB$_2$	LELRSB$_3$	LELRSB$_4$	LFEWCPSB$_1$	LFEWCPSB$_2$	LFEWCPSB$_3$	LFEWCPSB$_4$	LPEWSB$_1$	LPEWSB$_2$	LPEWSB$_3$	LPEWSB$_4$	
0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0, 0.2	0.8, 1, 1	0.6, 0.8, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0.2, 0.4	0.6, 0.8, 1	0.6, 0.8, 1	
0, 0.2, 0.4	0.6, 0.8, 1	0, 0.2, 0.4	0.2, 0.4, 0.6	0.8, 1, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1	0, 0.2, 0.4	0, 0.2, 0.4	
0, 0.2, 0.4	0, 0, 0.2	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0.8, 1, 1	0.6, 0.8, 1	0.6, 0.8, 1	0, 0.2, 0.4	0, 0, 0.2	0.6, 0.8, 1	0, 0, 0.2	
0, 0, 0.2	0.8, 1, 1	0, 0, 0.2	0.2, 0.4, 0.6	0, 0.2, 0.4	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.8, 1, 1	0.8, 1, 1	0, 0.2, 0.4	0.4, 0.6, 0.8	
0.2, 0.4, 0.6	0.6, 0.8, 1	0.8, 1, 1	0.8, 1, 1	0.6, 0.8, 1	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0.2, 0.4	0, 0.2, 0.4	0.4, 0.6, 0.8	0.2, 0.4, 0.6	
0.6, 0.8, 1	0.8, 1, 1	0.6, 0.8, 1	0.6, 0.8, 1	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0.6, 0.8, 1	0.6, 0.8, 1	0, 0.2, 0.4	0.8, 1, 1	0.4, 0.6, 0.8	
0, 0.2, 0.4	0, 0.2, 0.4	0.8, 1, 1	0, 0.2, 0.4	0.4, 0.6, 0.8	0, 0, 0.2	0.8, 1, 1	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0, 0.2	0, 0.2, 0.4	
0.8, 1, 1	0.2, 0.4, 0.6	0.6, 0.8, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.8, 1, 1	0, 0, 0.2	0.4, 0.6, 0.8	0, 0.2, 0.4	0.8, 1, 1	
0, 0, 0.2	0.4, 0.6, 0.8	0, 0, 0.2	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0, 0.2	
0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0, 0.2	0.2, 0.4, 0.6	0.8, 1, 1	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0, 0, 0.2	0.8, 1, 1	0, 0, 0.2	0.2, 0.4, 0.6	
0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0.8, 1, 1	0, 0, 0.2	0, 0, 0.2	0.8, 1, 1	0, 0, 0.2	0, 0, 0.2	0.4, 0.6, 0.8	0, 0, 0.2	
0.8, 1, 1	0, 0, 0.2	0.8,1,1	0.8, 1, 1	0.8, 1, 1	0.6, 0.8, 1	0.6, 0.8, 1	0, 0, 0.2	0.8, 1, 1	0, 0, 0.2	0, 0, 0.2	
0.2, 0.4, 0.6	0, 0.2, 0.4	0.2, 0.4, 0.6	0.6, 0.8, 1	0.2, 0.4, 0.6	0.8, 1, 1	0.8, 1, 1	0.8, 1, 1	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0, 0, 0.2	
0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0.2, 0.4	0, 0, 0.2	0, 0.2, 0.4	0.6, 0.8, 1	
0, 0, 0.2	0, 0, 0.2	0.8, 1, 1	0.4, 0.6, 0.8	0.8, 1, 1	0, 0, 0.2	0.8, 1, 1	0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0, 0, 0.2	
LEEPSB$_1$	LEEPSB$_2$	LEEPSB$_3$	LEEPSB$_4$	LAIFSB$_1$		LAIFSB$_2$	LAIFSB$_3$	LAIFSB$_4$	EPRSB$_1$	EPRSB$_2$	
0, 0.2, 0.4	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0.6, 0.8, 1		0.4, 0.6, 0.8	0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0, 0.2, 0.4	
0.8, 1, 1	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0, 0.2, 0.4		0.4, 0.6, 0.8	0.8, 1, 1	0.4, 0.6, 0.8	0, 0.2, 0.4	0.4, 0.6, 0.8	
0, 0.2, 0.4	0.8, 1, 1	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.2, 0.4, 0.6		0.4, 0.6, 0.8	0.6, 0.8, 1	0.6, 0.8, 1	0.8, 1, 1	0, 0.2, 0.4	
0.6, 0.8, 1	0, 0, 0.2	0.8, 1, 1	0, 0, 0.2	0.6, 0.8, 1		0.6, 0.8, 1	0, 0.2, 0.4	0, 0.2, 0.4	0.8, 1, 1	0.6, 0.8, 1	
0.4, 0.6, 0.8	0.6, 0.8, 1	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1		0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0, 0.2	0.4, 0.6, 0.8	0.4, 0.6, 0.8	
0, 0.2, 0.4	0, 0, 0.2	0, 0.2, 0.4	0.4, 0.6, 0.8	0.4, 0.6, 0.8		0, 0, 0.2	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0, 0.2, 0.4	0, 0.2, 0.4	
0.2, 0.4, 0.6	0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0, 0.2, 0.4		0.8, 1, 1	0.8, 1, 1	0, 0.2, 0.4	0.6, 0.8, 1	0.6, 0.8, 1	
0.4, 0.6, 0.8	0.4, 0.6, 0.8	0, 0, 0.2	0, 0.2, 0.4	0.6, 0.8, 1		0, 0.2, 0.4	0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0.6, 0.8, 1	
0, 0.2, 0.4	0.8, 1, 1	0, 0, 0.2	0, 0, 0.2	0.6, 0.8, 1		0.4, 0.6, 0.8	0, 0.2, 0.4	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.8, 1, 1	
0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1		0, 0.2, 0.4	0, 0.2, 0.4	0.8, 1, 1	0.6, 0.8, 1	0, 0, 0.2	
0.6, 0.8, 1	0.8, 1, 1	0.4, 0.6, 0.8	0.4, 0.6, 0.8	0.4, 0.6, 0.8		0.6, 0.8, 1	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1	0.2, 0.4, 0.6	
0, 0.2, 0.4	0.4, 0.6, 0.8	0.8, 1, 1	0.6, 0.8, 1	0.8, 1, 1		0.4, 0.6, 0.8	0, 0.2, 0.4	0.8, 1, 1	0.8, 1, 1	0.4, 0.6, 0.8	
0.2, 0.4, 0.6	0, 0.2, 0.4	0, 0.2, 0.4	0.4, 0.6, 0.8	0.4, 0.6, 0.8		0.4, 0.6, 0.8	0.8, 1, 1	0, 0.2, 0.4	0, 0, 0.2	0, 0, 0.2	
0.6, 0.8, 1	0.6, 0.8, 1	0.4, 0.6, 0.8	0.8, 1, 1	0, 0, 0.2		0, 0, 0.2	0.4, 0.6, 0.8	0.6, 0.8, 1	0, 0.2, 0.4	0, 0, 0.2	
0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0, 0.2, 0.4	0.6, 0.8, 1		0.8, 1, 1	0, 0.2, 0.4	0.8, 1, 1	0.4, 0.6, 0.8	0.8, 1, 1	

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