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Issues and solutions of electronic waste urban mining for circular economy transition: An Indian context

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ABSTRACT

The rapid consumption of advanced e-products has intensified problems for the linear economy; constantly diminishing natural resources employed in production processes have created a need of recycle and reuse. Although the transition to a circular economy proposes to end the loop of e-products, it needs the application of processes such as urban mining to recover resources as secondary raw material. The present study intends to examine the issues and challenges of electronic waste urban mining (EWUM) in India that need to be assessed for the development of a sustainable economy. To accomplish this, the current study employs integrated Multi-Criteria-Decision making methods (MCDM). Step-Wise Weight Assessment Ratio Analysis (SWARA) is used to prioritize issues and their possible solutions with Weighted Assessment Sum Product Assessment (WASPAS) methods introduced to explore these challenges and provide solutions for managing EWUM. There is an immediate need to acknowledge the issues confronted by stakeholders in urban mining processes for successful transition to a circular economy. A better understanding of the issues will help policy makers and decision makers to implement best practices to enhance the urban mining process in India. This study has shown that socio-economic (SE) issues are the most critical issues in EWUM in India. The possible solutions that would have most impact are to enhance awareness campaigns for people to educate themselves regarding e-waste, train staff to handle safe disposal of e-waste and produce eco-friendly electronic products.

Credit authorship

Conceptualization: MS, SJ, KG; Methodology: MS, SJ, KG; Formal analysis: MS; Investigation: MS; Resources: MS, SJ, KG; Writing – original draft: MS, SJ, KG; Writing – review & editing: MS, SJ, KG; Visualization: MS.

1. Introduction

A technological progression has seen an upsurge in the use of electrical and electronic equipment (EEE) with a resulting transformation in the lifestyle of people globally (Arya and Kumar, 2020; Awasthi and Li, 2018). The usage of EEEs like laptops, computers, notebooks and mobile phones has grown exponentially in the last decade, with sales of EEEs at 14.5 million units worldwide (Agrawal and Mittal, 2017; Sahajwalla and Gaikwad, 2018). The huge demand for better and more innovative electronic products worldwide has created a culture of obsolescence that is leading economies to rethink, re-plan, and reuse products by extracting the rare metals used. Some sectors in our societies are involved in the recycling with limited knowledge of advanced technologies and the safe handling of electronic waste (Borthakur, 2018). Moreover, the existence of dumping sites with municipal solid waste containing a major proportion of EEEs demonstrates the incompetent management of e-waste (Borthakur and Govind, 2017).

Urban mining is a concept developed from landfill mining; it aims to recover urban waste and use it where possible in supply chains (Arora et al., 2017; Mining, 2015). Since the 2000s, urban mining has been proposed for the extracting valuable metals such as copper and

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aluminum from waste (Tesfaye et al., 2017). Moreover, there is a greater content of rare earth metals present in industrial products as compared to raw ores. As they are in the form of refined metals, there is little energy needed for extraction as opposed to the huge amounts of energy required to smelt and refine ores (Zhanheng, 2011; Zeng et al., 2018). WEEE or e-waste contains precious metals but there are also some hazardous materials present that need to be handled safely. Urban mining with formalized processes for recycling e-waste can make a positive environmental impact and better economic results to achieve sustainable development goals (Sevigné-Itoiz et al., 2014).

Globally, India is in the top five producers of electronic waste; if this is not controlled or managed effectively, this may lead to a scarcity of resources for manufacturing electronic products in the future (Arya and Kumar, 2020). Although the government and policy-makers are aware of the electronic waste urban mining (EWUM) issues and have formulated appropriate policies, actual practices are still not acceptable. The reasons for low percentages of recycling in urban mining need to be investigated. The key issues in EWUM presently faced by stakeholders are examined in the current study. Also, how these challenges can be mitigated through possible solutions is evaluated. The present study attempts to identify and assess issues and their prospective solutions in EWUM in Indian context. The research objectives of the study are:

RO1: To examine the issues faced by stakeholders in the EWUM process that creates a bottleneck in the extraction of metals.

RO2: To evaluate alternative solutions to speed up the urban mining processes in developing countries like India.

To accomplish these objectives, an integrated SWARA-WASPAS approach is employed. The problems and possible solutions are extracted from a systematic literature review and substantiated by experts using the SWARA-WASPAS method. The contributions of the study are:

- This study identifies the issues faced by stakeholders in the EWUM processes and provides the best possible solution to enhance the process of urban mining.
- This study provides insights for policy-makers, manufacturing organizations, the wider community, recyclers, waste management companies, NGOs and other support organizations to manage electronic waste optimally.

The organization of the paper is segmented into 7 sections. Section 2 elaborates a review of literature on EWUM, the associated problems and possible solutions. Section 3 discusses the integrated research methodology implemented in the study. Section 4 expounds processes of SWARA and WASPAS methods. Section 5 elaborates on the application of research methods. The findings and results are discoursed in Section 6 and summarized in Section 7.

2. Literature review

The systematic literature review was performed to explore the problems in urban mining of e-waste. The study had selected undertaken two databases: Web of Science (WoS) and Scopus. The keywords selected include “urban mining”; “e-waste”; “e-waste management”; “recycling” and “WEEE urban mining”. The time limits were placed for the years 2016–2020. 1196 articles (WoS = 290; Scopus = 906) resulted from the first search. From these articles, 926 were selected after removing the common articles. The conference proceedings, book chapters, meta-analysis, review papers and conference papers were also excluded, resulting into 450 articles. The articles were scrutinized in context to our research questions and 79 papers were finally selected after thorough reading of the abstract. These 79 papers were directly related to our research questions and thus undertaken in the study to identify the issues and solutions in EWUM. This section has been categorized into sub sections to elaborate the current status of EWUM in developing countries.

2.1. Waste electrical and electronic equipment

WEEE also known as e-waste comprises all components, subcomponents and their parts discarded by the owners as waste” (Kumar et al., 2017). This definition describes a broad range of electronic devices such as mobile phones, computers, and other consumer electronics discarded by users (Jayaraman et al., 2019). The e-waste comprises of all the waste caused by castoff electronic products such as computers, mobile phones, laptops, printers, CDs and other accessories. This e-waste contains precious metals that can be extracted for reuse. But lack of knowledge and non-enforcement of environmental legislations, recycling and reuse practices are limited. The nature of the e-waste can be hazardous or non-hazardous with a mixture of ferrous and non-ferrous metals, wood, glass and ceramics. The main contributors to electronic waste are large and household appliances, lighting equipment, tools, toys, sports equipment and medical devices (Rao, 2014).

The electronic equipment is generally 50% percent ferrous metal, 13% non-ferrous and 12% plastic (Yunus and Sengupta, 2016; Turaga et al., 2019). Non-ferrous metals contain mainly heavy and precious metals such as lead, mercury, cadmium, zinc, copper, aluminium, silver, gold and selenium. But only 20% of the e-waste is recycled through proper channels (Chaudhary and Vrat, 2018).

2.2. Urban mining

The urban mining concept is in need of a circular economy to develop a policy framework for sustainable development (Silva et al., 2017). It helps to recover rare earth metals, polymers, ceramics, glass etc. via technological intervention (Sun et al., 2016). Urban mining through recycling processes is used to segregate components into metals, glass, polymers etc. whereas thermo-chemical, pyro-metallurgical, hydro-metallurgical and bio-metallurgical technologies may be utilized for resource extraction from the physical dispensation of electronic waste. The presence of polymers is also one of the main attractions as polymers can be reprocessed to develop new products. Printed circuit boards (PCB) are metal-polymer-glass fibre matrices that help in recovering metals, pyro-oil and glass fibre through mechanical separation (Khoshand et al., 2019).

The formal recycling process consists of manual segregation, mechanical separation, plastics recycling process and transportation of non-ferrous elements to metallurgical treatment plants for the separation of constituent metals. The low percentage of formal recycling is the main bottleneck in making the transition to a circular economy (Cesaro et al., 2018; Hu and Poustie, 2018).

a) Mechanical Separation: This is the first phase for recovery of metals in most developing countries like India. In this step, e-waste is dismantled and crushed manually using hammers, screw-drivers, pliers and other tools. Other more sophisticated methods such as magnetic, screening, eddy current and density separation are also applied.
b) Hydrometallurgical: The e-waste is exposed to leaching either in acid or caustic material during this process. The majority of formal recycling units in India practise this method; it is advantageous due to less risk of deadly and dust emissions, effective metal separation and negligible residue being left over.
c) Pyrometallurgy: The waste is heated in an inert gas atmosphere in this process. The extraction of PCB components is made through coal fired grills. The organic fractions such as paper, wood, rubber etc. are decomposed at higher temperatures; volatile substances that are formed can be utilized as chemical products.

Much informal recycling also takes place. This ‘Backyard Recycling’ involves collection, transportation, processing, segregation, repairing, refurbishing and dismantling in an informal way. The e-waste is managed by unscientific methods; 25–30% is reused with the remainder discharged into open dumps, streams, channels and open spaces. These methods are responsible for the deterioration and pollution of air, water and soil.

2.2.1. Issues encountered in urban mining in developing countries

Twenty percent of electronic waste produced globally is treated formally with the rest dumped or informally recycled (Zheng et al., 2018). The cost incurred in recycling or recovering is higher than the revenue generated through the extraction of metals (Bodsworth, 2018). Several developing countries have adopted Extended Producer Responsibility (EPR) policies but due to lack of formal treatment facilities and infrastructure, they face many challenges in the extraction of metals (Hu and Poustie, 2018). Other problems identified include public health and environmental issues, unsafe treatment practices of e-waste, informal hubs engagement and the collection and resale of e-waste informally (Ackah, 2017; Tong et al., 2018).

The other issue faced in urban mining is lack of coordination among formal channels, collectors, dismantlers and recyclers and with no prospect of a developing and integrated system approach (Ikhlayel, 2018). Non-reliable data on e-waste, non-identification of bulk consumers and inefficient audit procedures also create hurdles in the urban mining process. The informal sector collects e-waste and performs extraction without proper precautions such as safe handling or wearing gloves and masks (Nowakowski, 2017). Majority of the staff engaged in informal recycling is illiterate and unaware of proper disposal methods of electronic and hazardous substances. In recycling, cathode ray tubes (CRTs) are dismantled manually to isolate metals such as copper, with glass, circuit boards, gold plates, brass pins and condensers also recovered; practices involve soaking of pins in acid condensers, heating of microchips with acid for separation of metals (gold and brass); during this extraction process the release of toxic fumes is extremely harmful to the workers (Li et al., 2017). Besides the toxic inhalation of fumes and manual handling of dangerous materials, recycling practices do not adhere to legal regulations, with little regard to specific industrial, technology and classification standards (Huisman et al., 2019). The informal sector running recycling practices without proper licensing pose a major threat to the country's economy. There is an absence of stringent government regulations and centralized administration with no integrated or coordinated efforts from municipal corporations and their allied departments. The following issues are identified from previous studies and presented in Table 1.

The issues categorized in Table 1 are Socio-Economic (SE), Policy (PO), Technological (TE) and Environmental (EN). The first category is Socio-economic issues (SE); this includes outcomes of the ethical, political and theoretical practices resulting in a certain standard of treatment plus opportunities based on income and background. The second category is Policy (PO) issues; this includes policies of government, directions and legal framework prevailing in the country. The third category of issues is Technological (TE) relating to the technology framework. This category includes issues related to advance technical processes for urban mining and recycling. The fourth category is Environmental (EN) issues; this includes the hazardous nature of e-waste and the lack of the industry's commitment to implement environmental management practices.

2.3. Major initiatives across countries in e-waste management

Major initiatives such as the Basel Convention, Bamako Convention and Stockholm Convention have restricted the import of hazardous waste while taking measures to ensure protection of the environment (Lallas, 2001). The European Commission has adopted the Implementing Regulation (EU) 2019/290 that aims to harmonize all practices applied by member states for the registration and reporting of producers of EEE.

The StEP initiative is an independent, multi-stakeholder platform to address all dimensions of EEEs in a digitized world. StEP adopts UN

Table 1
Issues of electronic waste urban mining.

Code	Issue	Meaning	References
1. Socio-economic (SE) issues			
SE_1	Unorganized and informal e-waste recycling hubs	Disposal of e-waste is done through informal agencies, is highly fragmented and lacks monitoring	Ackah (2017); Tansel (2017); Awasthi and Li (2018). Yang et al. (2018)
SE_2	Improper health and safety measures	The disposal system includes burning and dumping in open sites. Safe techniques and practices are absent for handling e-waste	Kumar et al. (2019), Jayaraman et al. (2019); Awasthi et al. (2018a,b)
SE_3	Unskilled labor engaged in recycling	e-waste recycling is done by untrained workers	Goyal et al. (2018); Karmakar et al. (2018)
SE_4	Disposal of e-waste with regular municipal solid waste	e-waste is not disposed of separately. It is mainly done through landfilling	Ravindraand Mor (2019); Oluoko-Odingo and Mutisya (2019)
SE_5	Lack of inclusion of EEEs	Extractions are made difficult due to lack of knowledge of the contents of the product.	Ikhlayel (2018)
SE_6	Lack of conscientious group of people	Consumers dispose of e-waste inappropriately.	Borthakur and Govind (2018); Kumar and Rawat (2018)
SE_7	Unawareness about safe disposal process	The incorrect dismantling and processing, can lead toxic constituents to wreak havoc on human bodies	Ramzan et al. (2019); Jayaraman et al. (2019)
SE_8	Lack of experts to lead e-waste practices	The technical experts are failing to lead and implement safe practices	Ikhlayel (2018); Awasthi and Li (2018); Jayaraman et al. (2019)
SE_9	Non-identification of bulk customers	The bulk consumers generating e-waste need to be identified and dealt with separately.	Zeng et al. (2017); Sharma et al. (2020)
SE_{10}	Higher cost of recycling and extraction of metals	The formal process of extraction is more expensive.	Zeng and Li (2016); Zheng et al. (2018); Bodsworth (2018)
2. Policy issues (PO)			
PO_1	Illegal import of e-waste	Illegal shipment and dumping of electronic waste	Borthakur and Govind (2018); Ghosh (2019)
PO_2	Absence of government legislation to handle e-waste	Absence of strict legislation specifically for e-waste dumping and processing	Imran et al. (2017); Ilankoon et al. (2018) Krishnamoorthy et al. (2018);
PO_3	Lack of integrated system approach	Lack of formal integrated e-waste management system	Reddy (2016); Ikhlayel (2018); Xiao et al. (2018);
PO_4	Limited government financial support	The financial rewards are unattractive for recyclers	Xiao et al. (2018); Awasthi and Li (2018)
PO_5	Lack of comprehensive e-waste inventory/ statistical data	Due to informal recycling, the information is not visible in this informal system	Ikhlayel (2018)
3. Technological issues (TE)			
TE_1	Lack of formal treatment facilities and infrastructure for urban mining	The recycling process needs infrastructure and proper facilities	Hu and Poustie (2018); Gundupalli et al. (2018); Chaudhary and Vrat (2018);
TE_2	Lack of advance mining processes	Lack of technologies to mitigate the adverse effect of e-waste	Ramzan et al. (2019); Awasthi and Li (2018); Ghosh (2019); Dias et al. (2019)

(continued on next page)

Table 1 (*continued*)

Code	Issue	Meaning	References
1. Socio-economic (SE) issues			
TE_3	Communication gap between stakeholders	Lack of communication among the stakeholders for strategic planning	Awasthi and Li (2018); Turaga et al. (2019); Ikhlayel (2018).
TE_4	Lack of performance measurement systems	Lack of standards for measuring recycling process	Awasthi and Li (2018); Cucchiella et al. (2016) Kumar and Rawat (2018)
TE_5	Less skilled labor or staff	The labor is unskilled and untrained	Awasthi and Li (2018); Jayaraman et al. (2019)
TE_6	Lower percentage of extraction/treatment	A huge amount of metals remain unexplored due to inefficient treatments	Chaudhary and Vrat (2018)
4. Environmental dimension (EN)			
EN_1	Hazardous and harmful e-waste	Toxic elements such as mercury and lead should be tested and eliminated	Awasthi et al. (2018)
EN_2	Lack of contribution from manufacturing firms to adopt environmental management practices	Manufacturing organizations are not adopting eco-friendly practices; this means extraction of metal is becoming difficult.	Ravindra and Mor (2019)
EN_3	Lack of environmental indicators to assess harmful effects	There are no visible indicators showing how the environment is affected	Singh et al. (2018)

Sustainable Development Goals (SDGs) on responsible consumption and production. 24 kinds of solid waste including e-waste have been banned by China. China has also launched a scheme to create waste free cities, develop recycling bases and aim for zero waste imports. In India, e-waste management rules were enacted in 2016; these were amended in 2018 to create more effective and efficient e-waste management. This has become a worldwide issue and is significant in achieving SDG targets for 2030 - Goal 11 (Sustainable cities and Communities) and Goal 12 (Responsible Consumption and production) (Arya and Kumar, 2020).

International treaties such as EU directives, Basel Convention, Stockholm Conference etc. have considered the issue of e-waste and made regulations to better manage this issue. The WEEE directives have imposed stringent guidelines on any waste to be finally disposed of or landfilled. The Restriction of Hazardous Substances Direct (RoHS) directive has structured regulations towards ensuring public health, risk mitigation and limited usage of heavy metals such as palladium, mercury, cadmium and certain Polybrominated diphenyl ethers (PBDEs). The United Kingdom was the first to draft the law in 2005 ensuring that after manufacture, any products entering the European market should not contain hazardous metals. Switzerland was one of the earliest countries in the European Union to implement Extended Producer Responsibility (EPR). Germany has also adopted various effective measures - Act Governing the Sale, Return and Environmentally Sound Disposal of Electrically Sound Disposal of EEE (the ElektroG) in 2005. Japan has taken an initiative for e-waste recycling under 'Specifies Home Appliance Recycling Law' (SHARL) that looks at manufacturing of grey goods. Japan has also designed a coupon system for enhancing e-waste recycling. Norway has come up with an innovative model for e-waste, in which the distributor will receive e-waste at no cost. Further, in Korea and Taiwan, the producer finances the cost of recycling.

Developing nations have introduced sanitary landfilling and incineration as the main methods for waste disposal but unfortunately, this has led to an increment in toxic elements in the atmosphere (Lukose, 2015). A number of countries are still lacking stringent implementation of environmental rules (Krishnamoorthy, 2018).

2.3.1. Solutions to enhance urban mining in developing countries

Formal recycling units have been developed worldwide with established sites in countries such as China. For e-waste urban mining infrastructural development, there is a need to implement and integrate digital technologies that can transform informal recycling into a formalized and secure recycling sector. These technologies are expensive and thus require finance to be provided and managed by the government. As financial support from governments is often limited, a public-private partnerships (PPP) form of financing may be more effective (Gunarathne et al., 2019). A successful example of implementing the PPP model into the recycling industry in China has made a trail for other developing nations to generate and manage the finances needed. With an optimum amount of funds, the adoption of artificial intelligence agents such as robots can be implemented to extract materials such as aluminum, copper and gold from mobile phones to counter the problem of manual handling of hazardous metals during e-waste urban mining (Li et al., 2018). Another example of supporting recycling practices through advanced GIS tools for mapping urban mining is a project 'Wealth to waste' in Australia in 2015; this provides another opportunity for revolutionizing e-waste urban mining (Zhu, 2014). The government may also support urban mining by reducing tax on repaired products, with tax exemptions for workers or employees associated with repair services (Stahel, 2016). An incentive plan for the thousands of workers and urban local bodies or municipal corporations contributing to recycling will motivate them to enhance their efforts. The circular economy needs a restorative approach to develop reverse-cycle activities, which may in the longer term save billions of dollars of material costs (Chaudhary and Vrat, 2018; Mina et al., 2021) . The existing knowledge of the general population, as well as workers engaged in recycling activities, are not appropriate; public awareness campaigns are needed to communicate to people and workers regarding safe disposal of e-waste with personal protection (Ahmed, 2019; Shi et al., 2020). The focus of organizations must be to design eco-friendly products while considering the environmental challenges involved (Prodius et al., 2019).

2.4. Research gaps

Electronic waste management has been investigated in many studies during the last decade (Andrade et al., 2019). Different nations have analyzed management of e-waste in relation to their boundaries (Schumacher and Agbemabiese et al., 2019; Masud et al., 2019; Ismail and Hanafiah, 2019). Few researchers have conducted e-waste management issues though comparative analysis (Li et al., 2017; Sthiannopkao and Wong, 2013). Some researchers have discussed the challenges at both a national and international level with suggestions made for improving waste management practices. A few studies have elaborated on the complexity in e-waste management and its processes from generation to disposal (Kumar et al., 2017; Singh et al., 2019). The research area of electronic waste is not limited only to its management; treatment/disposal/recycling are new areas of concern (Duan et al., 2016; Li et al., 2019; Ismail and Huda, 2020). The impact of hazardous electronic waste and its effect on the environment has also been studied to assess the present conditions of EWUM (Li et al., 2019). Previous researchers have focused on a range of issues including optimization (Jouzdani and Govindan, 2021), country-specific supply chain mapping and the effects on human health, but the problems resulting from extraction of metals through urban mining in a developing economy is unexplored. Till now, no studies have been conducted to analyze the challenges faced in EWUM and also their possible solutions in India. This study aims to build a framework for EWUM for bridging this gap in current literature.

3. Research methodology

This section elaborated the methods undertaken for assessing the issues and solutions in EWUM discussed in section 2.1 and 2.2 and deciding their priorities. The SWARA methodology is used to compute the priorities of issues whereas the WASPAS method is applied to find the priorities of solutions to reduce the effect of the issues faced by stakeholders in e-waste urban mining. To investigate the issues and possible solutions to urban mining, a number of steps have been taken – experts and practitioners' responses on structured questionnaire, a study of recycling units, reports on e-waste management scrutinized and relevant databases examined. This section covers the elaboration of the methods used in the study, the data collection and expert selection.

3.1. Need of integrated approach; the SWARA-WASPAS method

MCDM methods are best at solving the complex, real problems faced by companies when many factors are involved (Barão et al., 2021; Kannan, 2021; Kannan et al., 2021; Govindan et al., 2021a). Managing e-waste issues are complex in nature and can be analyzed through MCDM methods (Sharma et al., 2020b).

The EUWM issues are analyzed through an integrated approach with problems analyzed through a SWARA method and solutions assessed using a WASPAS method (Ghenai et al., 2020; Shahnazari et al., 2020). The issues in e-waste management and urban mining are analyzed in past studies using Analytical Hierarchical Process (AHP), Analytical Network Process (ANP) and Interpretative Structural Modeling (ISM). The present study has two main objectives; a) exploring issues in EWUM b) assessing solutions with respect to the identified problems. The analysis of the issues from the first stage is explored in the second stage where the WASPAS method investigates the possible solutions.

3.2. Selection of experts

In India, Maharashtra, Tamil Nadu, Andhra Pradesh, Uttar Pradesh, West Bengal and Delhi are the top producers of e-waste. Maharashtra alone generates 396,000 Mt per year and presently has a 12% recycling capacity; Tamil Nadu is in second place with 260,000 Mt per year e−waste generation with 20.1% formal recycling capacity; this is followed by Andhra Pradesh with 250,000 Mt e-waste generation at only 4.72% formal recycling capacity. Delhi has the highest number of informal e-waste agencies, approximately 5000 in number. Uttar Pradesh, with the highest population in India, generates 202,000 Mt e-waste annually with a maximum formal recycling capacity of approximately 42.64% (Arya and Kumar, 2020).

This study has taken responses from the recyclers engaged in informal recycling of e-waste from three regions - Delhi, Mumbai and Uttar Pradesh. These three regions have high e-waste generation as well as a high capacity to recycle waste. The recycling units from these regions are the most appropriate for collecting data and exploring the problems faced by these firms/individuals in extracting the metals. These units/individuals are also aware of the current state of recycling, the harmful effects of informal recycling, basic infrastructure required, treatment processes etc. that may help to analyze the problems and solutions.

Based on previous studies, the SWARA method has been successfully used in various areas such as management, manufacturing, design, policy and environmental sustainability. This method is based on the implicit knowledge, experience and opinions of experts on a particular issue (Ghenai et al., 2020). The number of experts/decision-makers varies, as it does not have any defined rule for fixed values. The number of experts ranges from 3 to 15 in previous studies (Zolfani et al., 2013).

Few studies have categorized decision makers into two groups to enhance the reliability of the results. The two groups set up have equality in credibility and expertise.

The study has formed two groups including twelve experts. Both formal and informal recyclers, officers of municipal corporations, urban development staff, NGOs and a waste management scientist are regarded as experts to provide insights into the urban mining processes. Each group comprises of two academicians with relevant experience of more than 10 years, two experts from municipal corporations and two experts associated with government waste management projects; the groups include six managers from recycling units. The details of the experts are presented in Table 3.

Table 2
Solutions to enhance the e-waste urban mining.

Code	Solutions (S)	Implied meaning	References
S_1	Developing formal recycling networks	The informal recycling sector needs to be formalized for proper treatment of e-waste	Tong et al. (2018); Xiao et al. (2018); Turaga et al. (2019)
S_2	Application of digital technologies	Fostering use of advance technologies like internet, IoT and BDA in managing and treating e-waste	Zhu (2014); Alvarez-de-los-Mozos and Renteria (2017)
S_3	Assessing environmental indicators	The environmental indicators should be visible to assess the impact of e-waste	Ikhlayel (2018); Oluoko-Odingo and Mutisya (2019)
S_4	'Zero waste' concept/usage of secondary materials	Transforming existing cities and shifting towards low-to-no carbon cities.	Adeniran et al. (2017); Silva et al. (2017)
S_5	Usage of robots to extract materials	Using AI enabled robots can minimize harmful effects.	Alvarez-de-los-Mozos and Renteria (2017) Gundupalli et al. (2018); Li et al. (2018)
S_6	Developing regulatory framework	Developing regulatory framework to change consumer behavior.	Imran et al. (2017); Ilankoonet al., (2018); Arya and Kumar (2020)
S_7	Manufacturing eco-friendly products	Manufacturing organizations should implement practices to develop eco-friendly products/ design for environment products	Hu and Poustie (2018); Prodius et al. (2019)
S_8	Public awareness campaigns to educate people	More information campaigns to promote usage of eco-friendly products or design for environment products.	Borthakur and Govind (2018); Shi et al. (2020); Ravindra and Mor (2019);
S_9	Training support for workers for safe handling/disposal	Training for staff on safe handling, collection and disposal in recycling processes	Tansel (2017); Ikhlayel (2018)
S_{10}	Forming public private partnerships (PPP)	The integration of formal and informal sectors into a single unit	Xiao et al. (2018); Gunarathne et al. (2019)
S_{11}	Implementing extended producers' responsibility	For implementing EPR, it can mix economic, regulatory and voluntary dimensions	Gunarathne et al. (2019); Cao et al. (2016)
S_{12}	Incentives for recyclers, workers and municipal corporations	Financial incentives/ rewards for recyclers and ULBs for recycling	Cucchiella et al. (2016); Tesfaye et al. (2017)
S_{13}	Reward systems for consumers on product return	Financial rewards for consumers to return products for recycling	Hu and Poustie (2018); Tesfaye et al. (2017); Otto et al. (2018)

Table 3
Demographic profile of Experts.

Variables	Number of experts
GENDER	
Male	10
Female	2
AGE	
Less than 30 years	3
31-35 years	4
31-40 years	2
41-45 years	2
45 -55 years	1
EDUCATION	
Graduation (B.Tech)	6
Post-Graduation	4
Doctorate	2
EXPERIENCE	
Less than 5 years	0
6-10 years	6
11-15 years	5
More than 15 years	1
EXPERTISE	
Academics	2
Municipal corporation	2
Waste management project	2
Recycling units (Managers)	6

3.3. Integrated MCDM methods

The SWARA and WASPAS methods are discussed in sections 3.4.1 and 3.4.2.

3.3.1. Stepwise weight assessment ratio analysis (SWARA) method

This method is based on the importance of criteria assessed by the experts. Experts rank each criterion in order of preference based on their expertise (Zolfani, 2019). The criterion with maximum importance is rated as 1; the rest of the criteria are rated with respect to the first criterion. WASPAS is the most advanced MCDM approach with a high rate of accuracy. SWARA has previously been applied to sustainability and social responsibility issues (Karabasevic et al., 2015), the selection of green suppliers (Ghorabaee et al., 2016), service quality (Pamucar et al., 2019) and automatic vehicles (Zavadskas et al., 2018), supply chain survivability. The SWARA method is elaborated in the steps:

Step 1: Arranging criteria in descending order: The expert or decision-maker ranks the criteria in order of importance. The most important criterion is placed in the first order and sorted in descending order of importance. At the last place, the criterion is the least significant.

Step 2: Providing relative weighting for criteria. Once the overall ranking of the criteria has been determined, the decision makers compare the criteria. Therefore, the *j*-th criterion is compared to the *(j + 1)*-th criterion. This is called comparative advantage of the mean value (s_j).

Step 3: Co-efficient computation $\mathrm{k_j}$

After the comparison, the parameter $\mathrm{k_j}$ is calculated. The formula for $\mathrm{k_j}$ is shown in Eq. (1)

$$k_j = \begin{cases} 1 \mathrm{j} = 1 \\ \mathrm{s_j} + 1 \mathrm{j} > 1 \end{cases} \tag{1}$$

Step 4: The variable $\mathrm{q_j}$ is computed by Eq. (2)

$$q_j = \begin{cases} 1 \mathrm{j} = 1 \\ \dfrac{K_j - 1}{k_j} \mathrm{j} > 1 \end{cases} \tag{2}$$

Step 5: Computation of final weights.

The weights of the criteria are calculated by Eq. (3)

$$w_j = \frac{q_j}{\sum_{k=1}^{n} qk} \tag{3}$$

$\mathrm{w_j}$ is the relative weight of the *j-th* criterion. The priority vector is calculated by evaluating the criteria among themselves.

3.3.2. Weighted Assessment Sum Product Assessment (WASPAS)

WASPAS method has a combination of two models - the weighted sum model and the weighted product model. This method is the most appropriate MCDM technique for assessing the alternatives (Mardani et al., 2017). In this method, a decision matrix is developed where *n* represents the number of the alternatives, *m* defines the evaluation criteria and x_{ij} indicates the performance of the *i*th alternative with respect to the *j*th criterion (Prajapati et al., 2019). The method is categorized into the following steps.

Step 1: If beneficial criteria,

$$\widetilde{x}_{ij} = \frac{x_{ij}}{\max x_{ij}} \tag{4}$$

Step 2: If non-beneficial criteria

$$\widetilde{x}_{ij} = \frac{\min x_{ij}}{x_{ij}} \tag{5}$$

Step 3: Computation of total relative importance of ith alternative of WSM with the help from Eq. (6)

$$Q_i^{(1)} = \sum_{i=1}^{m} \widetilde{x}_{ij} w_j \tag{6}$$

Step 4: Computation of total relative importance of ith alternative of WPM with the help from Eq. (7)

$$Q_i^{(2)} = \sum_{i=1}^{m} \left(\widetilde{x}_{ij}\right) w_j \tag{7}$$

A joint generalized criterion of weighted aggregation of additive and multiplicative methods is proposed as follows;

$$Q_i = 0.5Q^{(1)} + 0.5Q^{(2)} = 0.5 \sum_{j=1}^{n} \widetilde{x}_{ij} w_{j+} 0.5 \sum_{j=1}^{n} \left(\widetilde{x}_{ij}\right)^{w_j} \tag{8}$$

Step 5: Final weights calculation with help from Eq (9)

$$Q_i = \lambda Q_i^{(1)} + (1 - \lambda) Q_i^{(2)} = \lambda \sum_{j=1}^{n} x_{ij} w_j + (1 - \lambda) \sum_{j=1}^{n} x_{ij}^{w_j} \tag{9}$$

4. Proposed research framework

The proposed research framework comprises of three stages. In the first phase, the critical issues of e-waste recycling in urban mining are identified and validated by experts. The second phase assesses the issues of EWUM using SWARA; the third phase examines solutions using the WASPAS method. Fig. 1 shows the proposed research framework for the current study.

4.1. Problem definition

From Table 4, it can be seen that Maharashtra is the main region for producing e-waste with the maximum number of authorized recyclers. Being the capital of India, Delhi has approximately 5000 informal recyclers. This study has looked at the regions of Maharashtra, Delhi and Uttar Pradesh where the number of authorized recyclers is high. These regions have recycling capacity for treating e-waste but still, only a small percentage is treated or recycled formally. There are reasons for the non-performance of recycling units that need to be identified through this study. Moreover, the solutions based on the identified issues may help policy-makers, stakeholders and society in general to implement sustainable practices in the future.

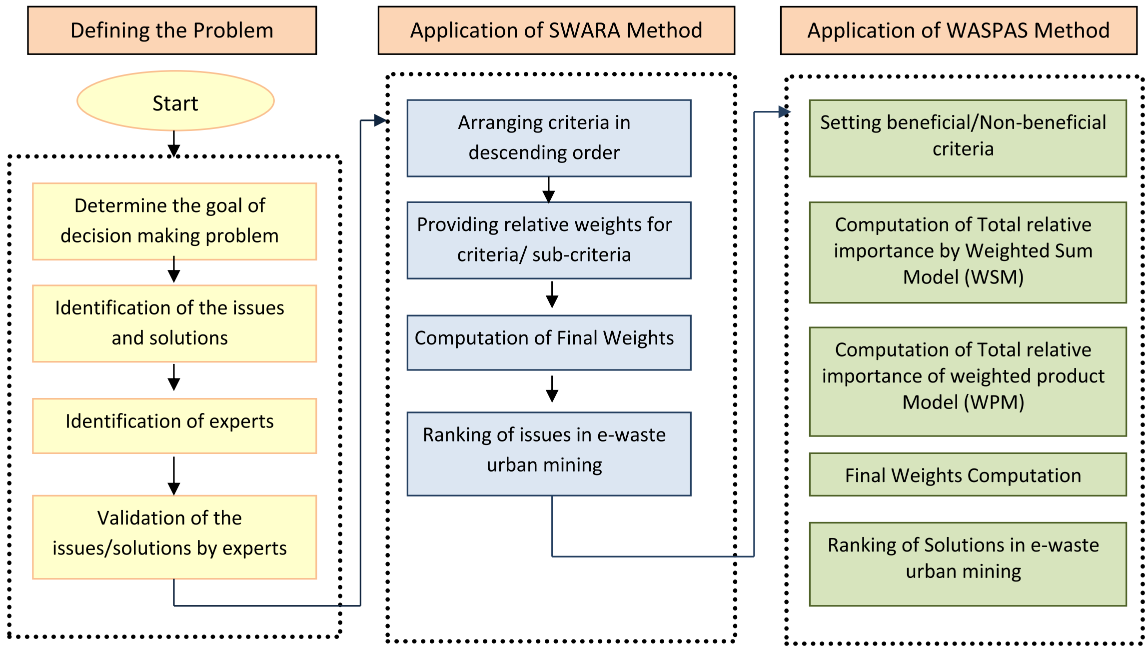

Fig. 1. Proposed Research framework.

Table 4
E-waste generation and recycling capacity in India (state wise).

Region	Quantity of E-waste (MTA)	Number of authorized recyclers	Waste recycled capacity (MT)
Andhra Pradesh	282266.4	01	480
Chhattisgarh	65186.14	01	600
Gujarat	2811925	16	49052.92
Goa	24,796	01	103
Haryana	58829.43	28	87,378
Himachal Pradesh	29029.38	01	1000
Jammu and Kashmir	1043.21	01	165
Karnataka	336791.6	71	52,722
Maharashtra	381686.2	75	78,179
Madhya Pradesh	125880.7	02	7600
Odisha	595697.8	03	3680
Punjab	115490.1	03	4850
Rajasthan	724663.2	26	90,769
Tamil Nadu	383189.2	24	97271.2
Telangana	277078.5	11	41,493
Uttar Pradesh	186,591	41	243627.5
Uttarakhand	24264.09	04	19,250
West Bengal	85848.74	03	1860
		312	782080.62

Ministry of Environment, Forest and Climate Change (MEFCC) (2019).

4.1.1. Phase 1: identification of challenges faced by stakeholders in EWUM

From the literature review, 24 problems are identified and examined; two groups of twelve experts each (as discussed in the previous section) are consulted. All these issues are categorized into four main categories, namely Socio-Economical (SE), Policy (PO), Environmental (EN) and Technological (TE). The detailed descriptions of 24 problems are listed in Table 3. A questionnaire is prepared and each group is asked to provide their responses (Appendix A; Tables A1, A3).

4.1.2. Phase 2: exploring possible solutions to minimize the challenges in EWUM

A total of 13 possible solutions have been explored from the literature review. The second part of the questionnaire is shared with the same group of experts to provide their preferences for the solutions (Appendix A; Tables A2, A4). The detailed list of solutions is presented in Table 4.

4.1.3. Phase 3: calculation of relative weights of problems using SWARA method

The calculation for the relative weights is conducted for two levels - the main criteria level and sub-criteria level. The groups of experts (EG1 and EG2) decide the average values for the main criteria and sub-criteria. The steps for weight calculation are followed as discussed in section 3.4.1. The judgments for the two expert groups EG1 and EG2 are merged via geometric mean. The weights of the main criteria are exhibited in Table 5. The computations based on EG1 responses are exhibited in Appendix B (Tables B1-B5).

The weights are obtained as per the steps discussed in Section 3.4.1 and shown in Table 6. The ranking of issues and solutions are ranked based on their relative weights. The global weights are exhibited in Table 7.

4.1.4. Phase 4: calculation of relative weights of solutions using WASPAS method

The solutions to the problems faced in e-waste urban mining are evaluated by the WASPAS method. Each solution is compared with the other solution against each issue and obtained value by both expert groups. The values of Q_1 and Q_2 using equations (7) and (8) are computed as discussed in section 3.4. The total relative significance Q_i is calculated using equations (8) and (9). The computations on the basis of group EG1 are shown in Appendix C (Tables C1-C4). Given the values of Q_i, the solutions are prioritized and exhibited in Table 7.

Table 5
Weights (main criteria).

Main Criteria	EG1	EG2	Geometric Mean
SE	0.519	0.514	0.516
EN	0.266	0.270	0.268
PO	0.140	0.139	0.139
TE	0.075	0.077	0.077

SE= Socioeconomic issues; EN = Environmental issues; PO=Policy issues; TE = Technological issues; EG1 = Expert group 1; EG2 = Expert group 2.

Table 6
Global weights.

Main criteria	Relative weight	EG1	EG2	Geometric mean
SE	SE_1	0.065	0.070	0.068
	SE_2	0.010	0.011	0.011
	SE_3	0.019	0.020	0.020
	SE_4	0.251	0.238	0.245
	SE_5	0.001	0.001	0.001
	SE_6	0.003	0.003	0.003
	SE_7	0.034	0.037	0.036
	SE_8	0.128	0.125	0.127
	SE_9	0.002	0.002	0.002
	SE_{10}	0.006	0.006	0.006
EN	EN_1	0.149	0.147	0.148
	EN_2	0.077	0.082	0.079
	EN_3	0.040	0.042	0.041
PO	PO_1	0.019	0.019	0.019
	PO_2	0.070	0.068	0.069
	PO_3	0.036	0.036	0.036
	PO_4	0.005	0.005	0.005
	PO_5	0.010	0.010	0.010
TE	TE_1	0.037	0.038	0.038
	TE_2	0.010	0.010	0.010
	TE_3	0.005	0.005	0.005
	TE_4	0.002	0.002	0.002
	TE_5	0.003	0.003	0.003
	TE_6	0.019	0.019	0.019

SE= Socioeconomic issues; EN = Environmental issues; PO=Policy issues; TE = Technological issues; EG1 = Expert group 1; EG2 = Expert group 2.

Table 7
Total relative significance.

Solutions	EG1	EG2	Geometric Mean	Priority
S_1	0.305	0.328	0.316	5
S_2	0.304	0.309	0.306	7
S_3	0.269	0.276	0.273	10
S_4	0.305	0.269	0.286	9
S_5	0.299	0.282	0.290	8
S_6	0.214	0.214	0.214	13
S_7	0.412	0.345	0.377	2
S_8	0.387	0.385	0.386	1
S_9	0.353	0.339	0.346	3
S_{10}	0.311	0.314	0.313	6
S_{11}	0.324	0.321	0.323	4
S_{12}	0.248	0.252	0.250	11
S_{13}	0.247	0.249	0.248	12

EG1 = Expert Group1; EG2 = Expert group 2.

5. Results and discussion

In the current study, based on the priorities calculated from SWARA and WASPAS methods, the problems and solutions are ranked. The SWARA method helps policymakers to identify those critical problems faced in EWUM. It creates a deeper understanding of the e-waste issues affecting the urban mining process; this in turn directly affects the waste management and resource implications of the economy (Kwatra et al., 2014). From Table 6, it is visible that Socio-economic (SE) issues are the most critical in EWUM followed by Environmental issues (EN), Policy (PO) and Technological (TE) issues. Each of the four criteria is also categorized into sub-criteria. The proposed solutions are also identified and presented in Table 2 after considering the issues from all four dimensions. WASPAS is applied sequentially and elaborated in Sections 3 and 4 to assess the solutions; the results are presented in Table 7. The most critical Socio-economic (SE) issues include 10 sub-criteria, from which, disposal of e-waste with regular waste (SE_4) has the highest global ranking followed by lack of experts to lead e-waste practices (SE_8); unorganized and informal e-waste recycling hubs (SE_1) with weightings of 0.2447, 0.1265 and 0.0675 respectively.

It has been observed through past research that people are unaware of disposal methods of electronic waste. Due to this lack of awareness related to separation and safe disposal of e-products, a huge quantity of electronic waste has been mixed in with municipal waste (Borthakur and Govind, 2017). More often, households dispose of their electronic waste in their dustbins with other domestic waste (Pradhan and Kumar, 2014). Due to the poor practices of the informal network of recyclers, e-waste is mixed with municipal waste and sent to landfill, increasing the environmental risks and health hazards (Aryan and Kumar, 2020).

The management of e-waste and urban mining needs experts to step up and lead good practice. A lack of participation by leading figures in the field has heightened the challenge in economies like India, Sri Lanka and other developing nations.

The majority of recyclers belong to informal networks in India, similar to many other developing nations. These informal networks are using traditional methods for extraction of metals through open burning, acid leaching, melting of plastic and open dumping of hazardous metals (Ilankoon et al., 2018). These informal networks are lacking in standardized, safe methods for the extraction of metals and are unaware of safe practices (Ravindra and Mor, 2019).

The main criteria of the environmental issue include three sub-criteria - harmful e-waste (E_2); lack of contribution from manufacturing firms to adopt environmental management practices (E_4); lack of environmental indicators (E_7); these are ranked at second, fourth and seventh places with weightings of 0.1480, 0.0790 and 0.0410 respectively. The use of traditional methods for extraction such as manual dismantling or open burning causes extreme harm to the health of recyclers, develop contaminations or infections in the environment that directly act as a source point for the spread of disease (Singh et al., 2018). Most of the informal networks in Delhi, Maharashtra and Uttar Pradesh are operating in residential areas without any safeguards or protection measures (Arya and Kumar, 2020). Based on the responses generated from recyclers during this study, it is visible that their awareness related to toxic nature of e-waste is very much limited. The recyclers are also unable to predict the long-term effects on the planet due to inappropriate e-waste handling, recycling and urban mining. These recyclers are also less aware of the possibility of recycling extracted metals for the development of new e-products (Sahajwalla and Gaikwad, 2018). They have no knowledge about plastics acting as a source for developing, constructing and producing other valuable materials (Meit, 2020; Islam et al., 2020).

The policy issue has 5 sub-criteria ranging from illegal import of electronic products (PO_1) to lack of comprehensive e-waste inventory/statistical data (PO_5). Absence of government legislations to handle e-waste (PO_2) and lack of integrated system approach (PO_3) are the two main critical barriers with weights of 0.0689 and 0.0358 respectively. The present e-waste policies and regulatory framework in India are less stringent. E-waste Amendment Rules, 2018, focused on implementing eco-friendly management of e-waste. But currently, there are a lack of initiatives shown by manufacturers and recycling units. The other problem area is the lack of an integrated approach throughout the nation. A coordinated approach for EWUM (PO_3) including government, manufacturers, business organizations, formal and informal recycling units, NGOs and public communities is needed to develop a core strategy for implementation of practices for urban mining at each level. At present, committed participation is missing.

The technological issue includes a lack of formal treatment facilities and infrastructure for urban mining (TE_1) and a lower percentage of e-waste being treated (TE_6). TE_1 has been ranked in eighth place with a weight of 0.0376. The management of electronic waste is more complex than for municipal waste and thus needs special methods for treating it. It is also essential to stop harming the environment. The infrastructure for advanced methods of treatment for formal recycling needs to be developed. The critical problems are in the following order as per their global rankings- SE4> EN1> SE8> EN2> PO2> SE1> EN3> TE1> PO3> SE7>SE3>PO1>TE6>SE2>PO5>TE2>SE10>PO4>TE3>SE6>TE5>SE9>TE4>SE5.

The issues faced by recycling units need to be minimized to mitigate harmful effects and to increase the levels of recovering precious metals through urban mining. A total of 13 solutions were analyzed through the WASPAS method in this study. The Q_i computations are considered to prioritize the solutions shown in Table 6; this gave the order - $S_8>S_7>S_9>S_{11}>S_1>S_{10}>S_2>S_5>S_4>S_3>S_{12}>S_{13}>S_6$. As per the value obtained by the WASPAS through expert responses, public awareness campaigns to educate people (S_8) received highest priority, followed by producing eco-friendly e-products (S_7); these were followed by training support for workers for safe handling/disposal (S_9), extended producer's responsibility (S_{11}), Developing formal recycling networks (S_1) and forming public private partnerships (S_{10}).

These solutions provide an insight for policymakers to focus on specific issues and their possible solutions to reassess the impact of electronic waste on the economy. With the help of these solutions, policy-makers can set out plans to reuse the maximum amount of resources in an efficient way where extraction can be carried out on a large scale with joint participation from the stakeholders (Govindan et al., 2021b).

The major issue of recycling units can be resolved through focused awareness campaigns for both the public and staff in the industry to handle and dispose of e-waste separately. The other possible solution lies in producing eco-friendly electronic products. Manufacturers have to design electronic products with less toxicity and should plan for recycling methods when they become obsolete. Further, formal recycling hubs should be enhanced for wider reach, proper treatment and urban mining of e-waste.

For the development of a successful integrated approach EPR, PPP, a skilled workforce, an educated public and advanced infrastructure are the key components.

6. Implications

The study has proposed a hybrid framework using SWARA and WASPAS to help policy makers and stakeholders, including municipal corporations, city planners and manufacturers, to understand the bottlenecks in EWUM. Urban mining is regarded as the latest battleground in protecting the environment, and in transitional economies like India, there is a key role to be played in achieving sustainability. EWUM is an emerging concern for developing countries to ensure the development of sustainable ecosystems but currently, due to the practices used in carrying out these processes, many problems have arisen for urban mining in India. The need is to remove the challenges related to reluctance to dispose of old electronic equipment among consumers in India. Equipment is kept even after it is not functional. In India, a core strategy needs to synchronize the umbrella strategies implemented by the government such as Swachh Bharat Abhiyan, Digital India and Make in India into one integrated model for treating e-waste; this needs to involve contributions from the manufacturers, recyclers and society at large. The vision of manufacturers should include the eco designing of electronic products with less toxic elements. This has to be supported by the government, policy-makers and involved organizations to increase awareness of the public towards disposal of e-waste; proper training of staff to handle and treat waste for extraction of metals must also be introduced. To tackle public awareness, campaigns should lead efforts in conducting activities and workshops to enhance outreach provision and to build capacity. The PPP and EPR collaborated approach should support policy-makers to integrate end users, manufacturers, recyclers, (informal and formal both) and NGOS to develop a synchronized, planned effort to conduct urban mining.

The stakeholders have a responsibility to decrease the quantity of e-waste and reuse in manufacturing electronic products. The use of secondary metals recovered through urban mining can be guided through a standardization of technologies that are used for extraction of metals during the recycling process. This study provides insight to policy makers, decision makers and other stakeholders to consider the bottlenecks in the urban mining process; there needs to be a focus on the possible solutions to reuse e-waste and reduce the detrimental effects on humans and the environment. If these issues are resolved, it will be beneficial for organizations and the public to compensate for the scarcity of mineral resources in India. Resources recovered from urban mining not only help to remove waste but also help to reduce the pollution that leads to health issues. More formalized recycling will enhance employment opportunities, reduce gas emissions, safeguard staff and contribute to a healthier and greener environment.

7. Conclusion

This study intends to analyze the problems and solutions affecting EUWM in the Indian context. Environmental concerns and scarcity of precious metals have made EWUM an economically viable solution. Presently, there is a need for more investigations to enhance the implementation of practices for the development of a healthier and more sustainable future. Making EWUM a formalized process with integrated and synchronized efforts of stakeholders, hybrid modeling and formal recycling networks will not only solve the issues of EUWM but also will help in developing a circular economy. The production of eco-friendly products will also help to reduce the burden on the environment and will enhance the extraction rate of metals from discarded products. EWUM has immense potential to extract resources and precious metals that may be used as a secondary source for manufacturing e-products. The implementation of effective EWUM practices provide a rich source of resources such as iron, copper, aluminum, lead, gold, silver and other valuable metals. An integrated approach will bring a change in the behavior and intention of the public to contribute to the environment and their society by recycling their e-waste. This is the right time to implement more stringent policies to encourage formal organizations to recycle and implement advanced techniques for enhancing urban mining through EPR, PPP and public communities.

However, the research has some limitations. This study is confined to a limited number of experts. More experts can be added to validate the results of the research study. The research framework has been developed in the context of a single country and thus it may be further tested in a range of different countries where conditions are similar.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
Problems in e-waste urban mining

Code	Problem	Implied meaning
Socio-economic barriers		
SE_1	Disposal of e-waste with regular municipal solid waste	The institutions, and the households without any segregation dispose the composite waste.

(continued on next page)

Table A1 (*continued*)

Code	Problem	Implied meaning
SE_2	Improper health and safety measures	The informal network engaged in the recycling process are not following any safety measures in handling hazardous e-waste
–	–	–
–	–	–
EN_3	Lack of environmental indicators	There are no indicators assessing the impact of e-waste urban mining processes on the environment.

Table A2
Solutions to e-waste urban mining

Code	Solutions
S_1	Formation of formal recycling networks
S_2	Industry 4.0 technologies
–	–
–	–
S_{13}	Reward system for product return

Questionnaire.

1. Industry ___
2. Age _____
3. Experience______
4. Please complete Table A3 as per the following steps based on the codes mentioned in Table 1A
   i. Arrange criteria (j) in descending order based on their relative significance
   ii. Assign the criteria with value; 1 (the highest importance)
   iii. From the second criterion onwards, please rate the relative significance of the criterion j w.r.t the (j+1) criterion.

Table A3
for SWARA calculation

Main criteria (problems)		Sub-Criteria						
Socio-economic barriers	Relative significance	Environmental issues	Relative significance	–	–	–	Technological issues	Relative significance

5. Please rate the solutions on a scale of 1–100 in Table A4 based on the problems mentioned in Table A3.

Table A4
WASPAS response sheet

Solutions	Code	Max/Min	Max/Min	–	–	–	–	Max/Min
		SE_1	SE_2	–	–	–	–	EN_3
Formal recycling networks	S_1							
Industry 4.0 …	S_2							
–								
–								
Reward system for product return	S_{13}							

Appendix B

Table B1
Computations for Experts group (EG1) using SWARA method

:	Calculation of main criteria (issues)			
Main criteria	Sj	kj	qj	Wj
SE	0.000	1.000	1.000	0.518
EN	0.950	1.950	0.512	0.265
PO	0.900	1.900	0.269	0.139
TE	0.850	1.850	0.146	0.075

Table B2
Sub-criteria Socio-Economic (SE) issues

SE issues	s_j	k_j	q_j	w_j
SE_4	0.000	1.000	1.000	0.485
SE_8	0.970	1.970	0.508	0.246
SE_1	0.950	1.950	0.260	0.126
SE_7	0.900	1.900	0.137	0.066
SE_3	0.850	1.850	0.074	0.036
SE_2	0.800	1.800	0.041	0.019
SE_{10}	0.850	1.850	0.022	0.011
SE_6	0.900	1.900	0.012	0.006
SE_9	0.850	1.850	0.006	0.003
SE_5	0.900	1.900	0.003	0.002

Table B3
Sub-criteria (Policy issues)

Policy issues	s_j	k_j	q_j	w_j
PO_2	0.0000	1.0000	1.0000	0.4987
PO_3	0.9500	1.9500	0.5128	0.2557
PO_1	0.9000	1.9000	0.2699	0.1346
PO_5	0.8500	1.8500	0.1459	0.0728
PO_4	0.9000	1.9000	0.0768	0.0383

Table B4
Sub-criteria (Technological issues)

Technological issues	s_j	k_j	q_j	w_j
TE_1	0.00	1.00	1.00	0.49
TE_6	0.97	1.97	0.51	0.25
TE_2	0.95	1.95	0.26	0.13
TE_3	0.90	1.90	0.14	0.07
TE_5	0.87	1.87	0.07	0.04
TE_4	0.80	1.80	0.04	0.02

Table B5
Calculation for Environmental issues

Sub criteria	s_j	k_j	q_j	w_j
EN_1	0.00	1.00	1.00	0.561
EN_2	0.95	1.95	0.513	0.288
EN_3	0.90	1.90	0.269	0.151

Appendix C

Table C1
The matrix for solutions for expert group (EG1)

	SE1	SE2	–	–	–	–	EN3
S_1	80	20		–	–	–	20
S_2	80	40	–	–	–	–	30
-	–	–	–	–	–	–	–
-	–	–	–	–	–	–	–
S_{13}	40	30					20

Table C2
Normalized matrix

	SE1	SE2	–	–	–	–	EN3
W_j	.067	.011	–	–		–	.041
S_1	.889	.22		–	–	–	.22
S_2	.889	.44	–	–	–	–	.33
-	–	–	–	–	–	–	–
-	–	–	–	–	–	–	–
S_{13}	.444						.22

Table C3
Calculation of total relative importance

	SE1	SE2	–	–	–	–	EN3
S_1	.060	.003	–	–	–	–	.001
S_2	.060	.005	–	–	–	–	.014
-	–	–	–	–	–	–	–
-	–	–	–	–	–	–	–
S_{13}	.029	–	–	–	–	–	.009

Table C4
Final weights calculation (According to Eq. (9)) for expert group 1

Solutions	$Q_i^{(1)}$	$Q_i^{(2)}$	Q_i
S_1	0.329	0.283	0.305
S_2	0.309	0.298	0.304
S_3	0.281	0.259	0.269
S_4	0.324	0.287	0.305
S_5	0.312	0.287	0.299
S_6	0.229	0.201	0.214
S_7	0.416	0.409	0.412
S_8	0.393	0.382	0.387
S_9	0.361	0.345	0.353
S_{10}	0.320	0.303	0.311
S_{11}	0.338	0.310	0.324
S_{12}	0.270	0.228	0.248
S_{13}	0.258	0.236	0.247

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