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The impact of engineering innovations on improving e-waste management

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Abstract
Engineering innovations are fundamentally advancing the management of electronic waste, transforming it from an environmental liability into an economic opportunity through smart technologies and sustainable design. This study evaluates public awareness, behaviors, and perceptions regarding e-waste, as well as the role of engineering solutions and regulations. A survey of 390 participants from diverse educational backgrounds (ranging from secondary to postgraduate levels) was conducted between January and April 2025. The results, quantified using the Weighted Arithmetic Mean (Grand Mean = 2.57), revealed a moderate to high level of knowledge about e-waste and its environmental impacts. A strong consensus emerged regarding the pivotal role of Green Engineering in sustainable development (Mean = 2.86). Participants identified advanced engineering solutions such as rare metal recovery and smart recycling as the most effective methods. A critical finding was that disposal behaviors are influenced more by the availability of specialized infrastructure than by awareness levels or costs. Furthermore, a significant willingness was observed among respondents to pay a premium for environmentally friendly devices, coupled with strong support for stringent regulatory laws ensuring manufacturer compliance. These findings highlight the necessity of an integrated strategy that synergizes technological innovation, effective policy enforcement, and targeted public awareness campaigns to establish a sustainable and circular framework for e-waste management.

Keywords: Circular Economy, Community Awareness, Electronic Waste, Engineering Innovations, Environmental Legislation.

تأثير الإبتكارات الهندسية في تحسين إدارة النفايات الإلكترونية

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الملخص

تُسهم الابتكارات الهندسية بشكل أساسي في تطوير إدارة النفايات الإلكترونية، وتحويلها من عبء بيئي إلى فرصة اقتصادية من خلال التقنيات الذكية والتصميم المستدام. قيّمت هذه الدراسة الوعي العام والسلوكيات والتصورات المتعلقة بالنفايات الإلكترونية، ودور الحلول واللوائح الهندسية. أُجري استطلاع رأي على 390 مشاركًا من خلفيات تعليمية متنوعة (من الثانوية إلى الدراسات العليا) بين يناير وأبريل 2025. كشفت النتائج، التي تم قياسها باستخدام المتوسط الحسابي المرجح (المتوسط الكلي = 2.57)، عن مستوى متوسط إلى مرتفع من المعرفة بالنفايات الإلكترونية وتأثيراتها البيئية. ظهر إجماع قوي على الدور المحوري للهندسة الخضراء في التنمية المستدامة (المتوسط = 2.86). حدد المشاركون الحلول الهندسية المتقدمة مثل استعادة المعادن النادرة وإعادة التدوير الذكية كأكثر الطرق فعالية. كانت النتيجة الحاسمة هي أن سلوكيات التخلص من النفايات تتأثر بتوفر البنية التحتية المتخصصة أكثر من تأثرها بمستويات الوعي أو التكاليف. علاوةً على ذلك، لوحظ استعدادٌ كبيرٌ لدى المشاركين لدفع مبالغ إضافية مقابل الأجهزة الصديقة للبيئة، إلى جانب دعمٍ قويٍّ لقوانين تنظيمية صارمة تُلزم المُصنِّعين بالامتثال لها. تُسلِّط هذه النتائج الضوء على ضرورة وجود استراتيجية متكاملة تواكب الابتكار التكنولوجي، والتطبيق الفعّال للسياسات، وحملات توعية عامة مُوجَّهة، من أجل إرساء إطار عمل مستدام ودائري لإدارة النفايات الإلكترونية.

الكلمات المفتاحية: الابتكارات الهندسية، الاقتصاد الدائري، التشريعات البيئية، الوعي المجتمعي، النفايات الإلكترونية.

Introduction

Engineering innovations are actively creating transformative solutions to address the escalating global crisis of electronic waste (e-waste). Artificial intelligence (AI) and robotics now enable high-precision sorting systems within recycling facilities. These advanced systems integrate hyperspectral imaging, deep learning algorithms, and robotic arms to automatically identify and separate components. They can distinguish more than 30 different material categories found in complex e-waste streams with remarkable accuracy. This automated sorting operates at high speeds—processing over 2 tons of e-waste per hour—and significantly outperforms manual methods [1].

Smart collection infrastructure, utilizing Internet of Things (IoT) sensors such as fill-level detectors installed in collection bins, is being deployed to optimize the logistics of e-waste gathering. These sensors provide real-time data that enable continuous monitoring and efficient route planning for collection vehicles [2]. The implementation of such smart systems reduces collection costs by an estimated 20–30%, while simultaneously increasing the capture rates of end-of-life electronics diverted from landfills [3].

Within the material recovery phase, advanced mechanical separation techniques are achieving unprecedented purity levels for recycled materials. Specifically, triboelectrostatic separation technology has demonstrated the capability to recover copper and plastic mixtures with purities exceeding 95%, enhancing the value and usability of recycled outputs [4].

Significant hydrometallurgical breakthroughs are also revolutionizing metal recovery, particularly through the use of novel solvents such as ionic liquids. These engineered solvents can extract gold from e-waste components with exceptional

efficiency, reaching approximately 99% recovery rates. Importantly, this method eliminates the need for highly toxic cyanide—traditionally used in gold leaching—thereby improving environmental and worker safety [5].
Biohydrometallurgy offers a promising and sustainable alternative, leveraging specially engineered strains of bacteria such as *Acidithiobacillus*. These microorganisms facilitate the bioleaching process to recover valuable metals like cobalt from complex components, including lithium-ion batteries. This biological approach achieves metal recovery at an estimated 40% lower energy cost compared to conventional pyro- or hydrometallurgical methods [6].
Innovations in thermal processing, including microwave-assisted pyrolysis, provide effective solutions for handling hazardous e-waste plastics. This technology efficiently converts brominated flame-retardant plastics into usable oil and gas products while capturing over 98% of the bromine content, thereby preventing the release of this toxic element into the environment [7]. Design engineering plays a vital preventive role in reducing future e-waste generation, primarily through the adoption of modular product architectures. Products such as Fairphone's repairable smartphones exemplify this approach, where modular design enables easy repair and component upgrades. This design philosophy demonstrably extends device lifespans by five years or more, significantly reducing the volume of discarded electronics [8]. Concurrent advances in materials science are also yielding environmentally friendlier alternatives for electronics manufacturing. These innovations include the development of biodegradable substrates—such as cellulose-based printed circuit boards (PCBs)—and safer soldering materials like lead-free tin–bismuth (Sn–Bi) alloys [9]. Automated disassembly is being revolutionized by robots equipped with advanced 3D vision systems. These robotic systems can disassemble devices at high throughput rates—for example, processing up to 400 smartphones per hour. A key capability of these systems is the safe and precise extraction of hazardous or high-value components, such as batteries, thereby improving worker safety and resource recovery efficiency [10].

Materials and Methods

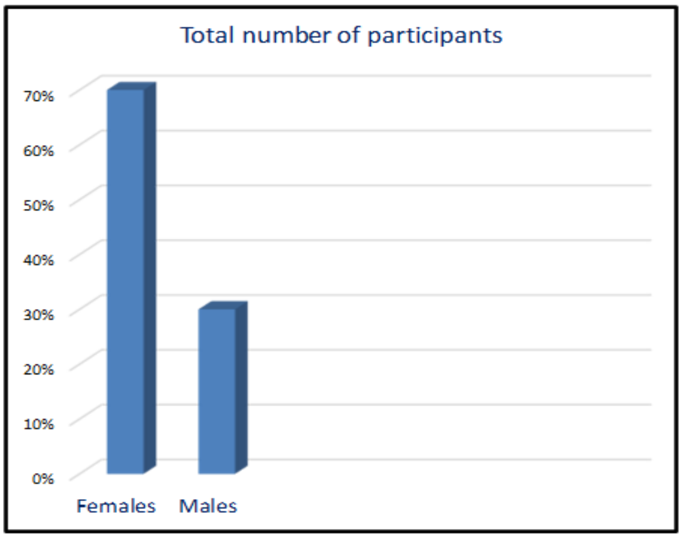
This study was conducted between January and April 2025 using an analytical–descriptive approach. It targeted a diverse cohort of participants with varied academic backgrounds. The sample comprised 390 randomly selected individuals to ensure comprehensive representation of the research variables. Table 1 presents the detailed structure of the questionnaire.

Table 1: Questions that make up the questionnaire structure.

No.	Question	Yes	No	I don't know
1	Do you have knowledge of the concept of engineering innovation?	76%	14%	10%
2	Are you aware of the environmental aspects of the Sustainable Development Goals (SDGs)?	68%	20%	12%
3	Do you believe that engineers play a key role in environmental protection?	83%	9%	8%
4	Do you think that engineering innovation contributes to reducing environmental pollution?	79%	11%	10%
5	Do you believe that your academic programs include sufficient topics related to environmental sustainability?	44%	41%	15%
6	Are you willing to participate in projects or research aimed at sustainable environmental solutions?	81%	8%	11%

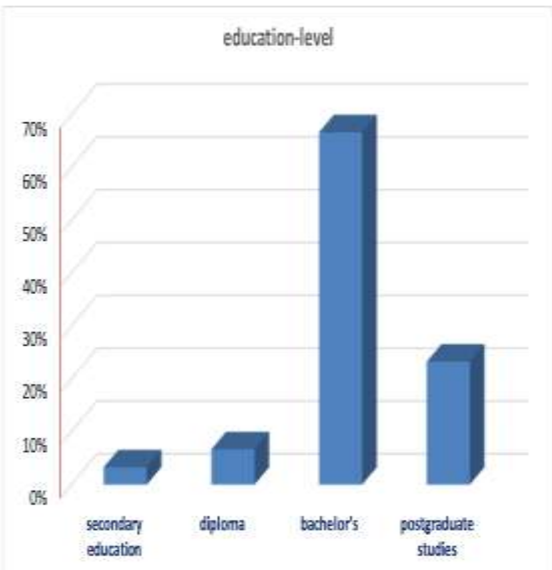
7	Do you think that lack of funding represents a challenge to implementing environmental innovation in the engineering field?	66%	24%	10%
8	Does low environmental awareness hinder the implementation of engineering innovation?	61%	28%	11%
9	Do you believe that clean energy technologies are among the most important engineering innovations for achieving sustainable development?	88%	7%	5%
10	Do you think that green engineering supports sustainable development?	91%	5%	4%

Data collection utilized Google Forms for accessibility, disseminated via email and social media, yielding 390 participants (117 males [30%], 273 females [70%]; Figure 1.



Figures 1: Gender distribution.

Random sampling ensured representation across academic tiers, including secondary education (n = 13), diploma (n = 26), bachelor's (n = 260), and postgraduate studies (n = 91). The varying participation rates by education level (Figure 2) reflect demographic engagement and reinforce the analytical rigor of the study.



Figures 2. Education-level participation

Results and Discussion

The Statistical Package for the Social Sciences (SPSS) was used to analyze the data, employing a three-point Likert scale to measure the level of awareness among engineering college students regarding electronic waste. Responses were based on a triple-choice format—**Yes**, **I don't know**, and **No**—which were assigned scores of 3, 2, and 1, respectively. This scoring system enabled the calculation of the weighted arithmetic mean and standard deviation, allowing for the determination of the sample's overall tendencies and the ranking of each question, as presented in Table 2.

Table (2): Calculation of the Weighted Arithmetic Mean.

Opinion	No	I don't know	Yes
Weighted Mean Range	1.0 - 1.66	1.67 - 2.33	2.34 - 3.0

Reliability was confirmed via Cronbach's Alpha (α = 0.829), indicating high measurement consistency.

Based on the results presented in Table 3, the analysis of survey responses—quantified using the Weighted Arithmetic Mean—revealed critical insights into stakeholder perceptions. The strongest consensus emerged for Question 10, which addressed the role of Green Engineering in supporting sustainable development and achieved the highest mean score (2.86). This overwhelming agreement (91% "Yes") underscores a well-recognized synergy between green engineering principles and sustainable development goals, a connection reinforced by foundational frameworks such as the **Circular Economy Action Plan** [12].

In contrast, Question 5, which examined the adequacy of environmental sustainability topics in academic curricula, received the lowest mean score (2.03), reflecting an overall "I don't know" tendency. This notable gap highlights a major deficiency in current educational programs that fail to adequately equip students with the knowledge required to advance sustainable e-waste management—a field that increasingly depends on engineering innovations such as AI-based sorting systems [1, 3] and advanced metal recovery techniques [5, 6, 11].

Table (3): Calculation of the arithmetic mean and standard deviation.

Question	Yes	don't know	No	Sample size	arithmetic mean	standard deviation
1	296	39	55	390	2.62	0.72
2	265	47	78	390	2.48	0.81
3	324	31	35	390	2.74	0.61
4	308	39	43	390	2.68	0.66
5	172	59	160	390	2.03	0.92
6	316	43	31	390	2.73	0.60
7	257	39	94	390	2.42	0.85
8	238	43	109	390	2.33	0.88
9	343	20	27	390	2.81	0.54
10	355	16	20	390	2.86	0.47
					2.57	0.71

The overall positive tendency of the sample (Grand Mean = 2.57) toward the survey themes indicates a strong receptiveness to engineering-based solutions. This finding aligns with participants' identification of advanced technologies—such as rare metal recovery and smart recycling—as highly effective strategies. However, this positive disposition is moderated by the presence of infrastructural and educational barriers. The preference for engineering-driven approaches directly correlates with technological advancements documented in the literature, including smart collection systems employing IoT sensors [2, 3] and automated disassembly robotics [10], both of which are pivotal for advancing a circular economy in e-waste management [9].

Conclusions

In conclusion, this study demonstrates that engineering innovations are pivotal in catalyzing a paradigm shift in electronic waste management, transforming environmental liabilities into valuable economic assets. Conducted between January and April 2025 with a diverse cohort of 390 participants, the research reveals a strong stakeholder preference for high-impact engineering solutions, particularly rare metal recovery and smart recycling. However, the effectiveness of these technological advancements is constrained by persistent infrastructure deficiencies and low formal recycling rates. A key finding indicates that access to specialized infrastructure exerts a stronger influence on disposal behaviors than individual awareness alone. This underscores the urgent need for strategic investment in and deployment of advanced systems—such as IoT-enabled collection networks and automated disassembly robotics—to bridge the implementation gap. Achieving sustainable e-waste management, therefore, requires an integrated approach that concurrently advances engineering innovation, enforces robust environmental legislation, and strengthens targeted public awareness initiatives to foster a collaborative ecosystem for a circular economy.

Recommendations

1. Support engineering innovations by developing and implementing advanced technologies for rare metal recovery and smart recycling, thereby contributing to environmental sustainability and the creation of economic value.
2. Enhance infrastructure through the establishment of specialized facilities for the collection, sorting, and treatment of electronic waste, enabling more effective and efficient environmental management.
3. Promote community awareness through targeted media campaigns and educational programs that highlight the risks associated with electronic waste and emphasize safe disposal practices.
4. Provide financial incentives and support programs that encourage consumers to select environmentally friendly devices, thereby stimulating market demand for sustainable production and responsible consumption.
5. Expand future research to include more diverse demographic groups and geographical regions, with a focus on identifying and analyzing the key factors influencing environmental behaviors toward electronic waste management.

References

[1] Kang Liu, Quanyin Tan, Jiadong Yu, Mengmeng Wang (2023), A global perspective on e-waste recycling, Circular Economy, Volume 2, Issue 1, March, https://doi.org/10.1016/j.cec.2023.100028.

[2] Valerio Elia, Maria Grazia Gnoni, and Fabiana Tornese, Designing a sustainable dynamic collection service for WEEE: an economic and environmental analysis through simulation, Waste Management & Research: The Journal for a Sustainable Circular Economy Volume 37, Issue 4, https://doi.org/10.1177/0734242X19828121

[3] David B. Olawade, Oluwaseun Fapohunda, Ojima Z. Wada, Sunday O. Usman, Abimbola O. Ige, Olawale Ajisafe, Bankole I. Oladapo (2024), Smart waste

management: A paradigm shift enabled by artificial intelligence, Waste Management Bulletin, Volume 2, Issue 2, June 2024, Pages 244-263, https://doi.org/10.1016/j.wmb.2024.05.00.

[4] M. F. Boukhoulda, M. Rezoug, W. Aksa, M. Miloudi, K. Medles &L. Dascalescu (2017), Triboelectrostatic separation of granular plastics mixtures from waste electric and electronic equipment, Particulate Science and Technology, An International Journal, Volume 35, Issue 5, Pages 621-626, DOI: 10.1080/02726351.2017.1347226.

[5] Aradhana V. Thombre & Debashis Kundu (2023), Ionic liquid promoted extraction of gold from electronic waste: a modeling study, Separation Science and Technology, Volume 58, Issue 15-16, https://doi.org/10.1080/01496395.2023.2223759.

[6] Arda Işıldar, Eric D. van Hullebusch, Markus Lenz, Gijs Du Laing, Alessandra Marra, Alessandra Cesaro, Sandeep Panda, Ata Akcil, Mehmet Ali Kucuker, Kerstin Kuchta (2019), Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) – A review, Journal of Hazardous Materials, Volume 362, January, Pages 467-481, https://doi.org/10.1016/j.jhazmat.2018.08.050.

[7] Andrea Undri, Luca Rosi, Marco Frediani, Piero Frediani (2014), Microwave assisted pyrolysis of corn derived plastic bags, Journal of Analytical and Applied Pyrolysis, Volume 108, July 2014, Pages 86-97, https://doi.org/10.1016/j.jaap.2014.05.013.

[8] Bovea, M. D., Pérez-Belis, V., & Quemades-Beltrán, P. (2017), Attitude of the stakeholders involved in the repair and second-hand sale of small household electrical and electronic equipment: Case study in Spain. Journal of Environmental Management, 196, 91-99. https://doi.org/10.1016/j.jenvman.2017.02.069.

[9] Cucchiella, Federica & D'Adamo, Idiano & Lenny Koh, S.C. & Rosa, Paolo, 2015. "Recycling of WEEEs: An economic assessment of present and future e-waste streams," Renewable and Sustainable Energy Reviews, Elsevier, vol. 51, pages 263-272, DOI: 10.1016/j.rser.2015.06.010.

[10] Supachai Vongbunyong & Wei Hua Chen (2015), Disassembly Automation, Part of the book series: Sustainable Production, Life Cycle Engineering and Management ((SPLCEM)), pp 25–54.

[11] Moisés Gómez, Sue Grimes, Geoff Fowler (2024), Development of complete hydrometallurgical processes for gold recovery from ICs and CPUs using ionic liquids, Journal of Environmental Management, Volume 362, June, https://doi.org/10.1016/j.jenvman.2024.121306.

[12] Circular Economy Action Plan International aspects (2020), Publications Office of the EU, ISBN 97B-92-76-21692-6.