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From Waste to Wealth: Leveraging Upcycling to Drive Sustainable E-Waste Management

Od odpadów do bogactwa: wykorzystanie upcyklingu do wspierania zrównoważonego gospodarowania odpadami elektronicznymi

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Abstract
Electronic waste (e-waste) is one of the fastest-growing environmental challenges globally, posing significant threats to ecosystems and public health. This study explores the potential of upcycling as a sustainable solution to mitigate the adverse impacts of e-waste. Upcycling, unlike conventional recycling, transforms discarded materials into products of higher value, aligning with circular economy principles. Using a comprehensive dataset spanning multiple regions and years (2010–2023), this research examines the effectiveness of upcycling in reducing carbon footprints, managing toxic components, and generating economic opportunities. The analysis reveals that 33% of e-waste in the dataset underwent upcycling processes, predominantly in developed regions such as London and Berlin, which demonstrated lower carbon footprints compared to developing areas like Mumbai and Dhaka. Additionally, upcycling was associated with significant reductions in toxic components like lead and mercury, highlighting its environmental benefits. The study also identifies key regional disparities and trends, emphasizing the need for tailored policies and investment in sustainable waste management infrastructure. By integrating advanced upcycling techniques into existing waste management systems, policymakers can address environmental concerns while fostering economic growth. This research contributes to the ongoing discourse on sustainable development by providing actionable insights into the role of upcycling in e-waste management. The findings underscore the importance of adopting innovative strategies to achieve ecological sustainability and economic resilience in the face of mounting e-waste challenges.

Key words: upcycling, e-waste, sustainable development, circular economy, carbon footprint reduction, toxic components management

Streszczenie
Odpady elektroniczne (e-odpady) stanowią jedno z najszybciej rosnących wyzwań środowiskowych na świecie, zagrażając ekosystemom i zdrowiu publicznemu. Niniejsze badanie analizuje potencjał upcyklingu jako zrównoważonego rozwiązania w celu ograniczenia negatywnego wpływu e-odpadów. Upcykling, w odróżnieniu od tradycyjnego recyklingu, przekształca wyrzucone materiały w produkty o wyższej wartości, zgodnie z zasadami gospodarki o obiegu zamkniętym. Wykorzystując kompleksowy zbiór danych obejmujący wiele regionów i lat (2010–2023), badanie ocenia skuteczność upcyklingu w redukcji śladu węglowego, zarządzaniu toksycznymi składnikami oraz generowaniu możliwości ekonomicznych. Analiza pokazuje, że 33% e-odpadów w zestawie danych poddano procesom upcyklingu, głównie w rozwiniętych regionach takich jak Londyn i Berlin, które charakteryzowały się niższym śladem węglowym w porównaniu z obszarami rozwijającymi się, takimi jak Mumbaj i Dhaka. Dodatkowo upcykling przyczynił się do znacznej redukcji toksycznych składników, takich jak ołów i rtęć, co podkreśla jego korzyści środowiskowe. Badanie identyfikuje również kluczowe różnice regionalne i trendy, podkreślając potrzebę dostosowanych polityk i inwestycji w zrównoważoną infrastrukturę zarządzania odpadami. Integracja zaawansowanych technik upcyklingu z istniejącymi systemami zarządzania odpadami może pomóc decydentom w rozwiązywaniu problemów środowiskowych, jednocześnie wspierając wzrost gospodarczy. Niniejsze badanie wnosi istotny wkład w dyskusję na temat zrównoważonego rozwoju, dostarczając praktycznych wskazó-

wek dotyczących roli upcyklingu w zarządzaniu e-odpadami. Wyniki podkreślają znaczenie wdrażania innowacyjnych strategii na rzecz ekologicznej stabilności i resilencji ekonomicznej w obliczu rosnących wyzwań związanych z e-odpadami.

Słowa kluczowe: upcycling, odpady elektroniczne, zrównoważony rozwój, gospodarka o obiegu zamkniętym, redukcja śladu węglowego, zarządzanie toksycznymi składnikami

1. Introduction

The growing challenge of electronic waste: Electronic waste (e-waste) is one of the fastest-growing waste streams globally, driven by rapid technological advancements and the increasing consumption of electronic devices. It is expected to exceed 74 million metric tons by 2030. Improper disposal of e-waste not only contributes to resource depletion but also poses significant environmental and health risks due to the presence of hazardous materials such as lead, mercury, and cadmium. Despite the severity of this issue, global e-waste recycling rates remain alarmingly low, with only 17.4% of e-waste being formally recycled in 2019 (Forti et al., 2020). This highlights the urgent need for innovative waste management strategies that align with principles of sustainability and circular economy.
What is upcycling? Upcycling represents a transformative approach to waste management, wherein discarded materials are repurposed into products of higher quality or value. Unlike traditional recycling, which often downgrades the material's quality, upcycling enhances both the functional and aesthetic value of waste materials (Sung, 2015). This process not only reduces waste volume but also contributes to economic and environmental sustainability. In the context of e-waste, upcycling has the potential to address multiple challenges, including the conservation of valuable resources, reduction of landfill dependency, and minimization of environmental contamination. By focusing on reimagining the utility of outdated electronic devices, upcycling offers a practical solution to the e-waste crisis (Hahladakis et al., 2020).
E-waste in the circular economy: The circular economy emphasizes resource efficiency and waste minimization by promoting the continuous use of materials. Within this framework, upcycling plays a critical role by extending the lifecycle of electronic components and reducing the need for virgin raw materials (Ellen MacArthur Foundation, 2019). For instance, integrating upcycling practices into e-waste management could reduce greenhouse gas emissions and create sustainable economic opportunities. However, challenges such as the heterogeneity of e-waste and the lack of standardized policies hinder the widespread adoption of upcycling. Addressing these barriers requires coordinated efforts among governments, industries, and consumers (Parajuly et al., 2020; Priyan et al., 2025).
Environmental benefits of upcycling e-waste: Upcycling offers substantial environmental advantages by diverting e-waste from landfills and incineration, thereby reducing pollution and conserving natural resources. Studies have shown that upcycling can lower the carbon footprint of electronic products by up to 40% compared to traditional recycling methods (Singh et al., 2021). Moreover, it mitigates the release of toxic substances into ecosystems, safeguarding public health and biodiversity (Zhou et al., 2022). By promoting cleaner production and sustainable consumption patterns, upcycling aligns with global sustainability goals and fosters resilience in waste management systems (Hahladakis et al., 2020).
Economic opportunities through upcycling: The economic implications of upcycling are equally compelling. Upcycling not only creates new markets for innovative products but also drives job creation and entrepreneurship. In developing regions, where informal e-waste recycling often prevails, upcycling can formalize operations and improve working conditions (Raghupathy & Chaturvedi, 2020; Ince, 2024). Furthermore, consumer demand for eco-friendly and ethically produced goods has accelerated the growth of the global upcycling market. This trend underscores the economic viability of integrating upcycling into mainstream e-waste management practices (Statista, 2023).
Social impact of upcycling: Upcycling also holds significant social value by promoting inclusivity and empowering marginalized communities. Informal e-waste workers, often exposed to hazardous conditions, can benefit from safer practices and fair wages through upcycling initiatives (Wilson et al., 2018). These initiatives also foster skill development and community engagement, enhancing social equity. By bridging the gap between environmental sustainability and social justice, upcycling addresses broader development challenges and aligns with the United Nations Sustainable Development Goals (SDGs).
The practice of upcycling in the context of electronic waste management aligns with several of the United Nations Sustainable Development Goals (SDGs). SDG 12: Responsible Consumption and Production is particularly relevant as upcycling directly contributes to the sustainable management of resources by promoting the reuse of e-waste and minimizing the environmental impact of waste. By reusing materials and components from electronic devices, upcycling reduces the need for raw materials, conserving natural resources and reducing the carbon footprint associated with the production of new electronics (Yoshida et al., 2016; UNEP, 2021).
Moreover, SDG 13: Climate Action is closely linked to the practice of upcycling in e-waste management. The reduction in the disposal of electronic waste, as well as the reduction of carbon emissions associated with new

production processes, supports global efforts to combat climate change. Upcycling e-waste helps mitigate the environmental degradation caused by the accumulation of electronic waste in landfills, which is a significant source of methane and other greenhouse gases (Clark & Wu, 2016; Schluep et al., 2020). By transforming waste into valuable resources, upcycling contributes to both environmental sustainability and climate action.
In addition, SDG 8: Decent Work and Economic Growth is relevant to upcycling as it creates opportunities for local economies and informal sectors involved in e-waste recycling and upcycling. The process generates job opportunities in the repair, remanufacturing, and reuse of electronic components, contributing to sustainable economic growth. The upcycling industry fosters green jobs, which are crucial for transitioning to a low-carbon economy (Jayaraman et al., 2021).
Finally, SDG 10: Reduced Inequalities is pertinent when considering how upcycling e-waste can support social justice. Many marginalized communities in developing countries are impacted by the improper disposal of e-waste, which exposes them to hazardous materials. Upcycling, therefore, not only provides an environmentally friendly solution but also offers an avenue to reduce inequality by creating safer working conditions and providing access to more sustainable livelihoods for vulnerable populations involved in e-waste management (Baldé et al., 2017). Also, e-waste can serve as an aggregate material in composite structures, contributing to a cleaner built environment while supporting the achievement of the SDGs (Priyan et al., 2025).
Research gaps in upcycling: Despite its potential, upcycling remains underutilized in e-waste management. Key research gaps include the lack of metrics to evaluate its environmental and economic impacts, limited scalability, and insufficient policy frameworks to support its implementation (Parajuly et al., 2020). Addressing these gaps requires interdisciplinary research and collaboration among stakeholders. Emerging technologies, such as artificial intelligence and blockchain, present new opportunities to optimize upcycling processes. For instance, AI can enhance material recovery, while blockchain ensures transparency and traceability in upcycled products (Kumar et al., 2022).
The impact of Covid-19 pandemic on upcycling: The pandemic had significant effects on the generation of electronic waste worldwide. At the beginning of the pandemic, lockdowns and stay-at-home orders led to a slowdown in production processes, and in some cases, temporary suspension of electronic device manufacturing. This resulted in a short-term decline in e-waste generation (Baldé et al., 2020).
However, as the pandemic continued, the demand for digital services such as remote working and online education increased, leading to a surge in the need for new electronic devices. This led to a faster replacement of old devices and, consequently, a rebound in e-waste production (Schluep et al., 2020). For instance, in 2020, it was obtained that 53.6 million metric tons of e-waste were generated globally (Baldé et al., 2020). In 2021 and 2022, this number was seen to rise to 57.4 million tons and 62 million tons, respectively (UNEP, 2021; Selvakumar et al., 2025). Furthermore, the pandemic also saw an increase in medical waste, particularly masks, gloves, and other protective equipment, which created additional challenges for waste management systems (Schluep et al., 2020). This further stressed the need for integrated waste management strategies that address both e-waste and medical waste.
Overall, the impact of Covid-19 on e-waste production has been complex and multi-faceted, with periods of decline followed by rapid increases as the demand for new technology grew. Understanding the long-term consequences of these shifts requires further research to develop sustainable e-waste management strategies in response to these evolving challenges (Baldé et al., 2020; UNEP, 2021).
Purpose of the study: This study explores the role of upcycling in sustainable e-waste management, with a focus on its environmental, economic, and social impacts. By leveraging data-driven insights, it aims to provide actionable recommendations for integrating upcycling into global waste management strategies. Ultimately, the research seeks to demonstrate how upcycling can transform the e-waste crisis into opportunities for sustainability and innovation.

2. Methodology

2.1.Research design
This study adopts a mixed-methods approach, combining quantitative and qualitative analyses to investigate the role of upcycling in sustainable e-waste management. By leveraging a robust dataset and interdisciplinary frameworks, the research aims to evaluate environmental, economic, and social impacts of upcycling practices. The primary focus is on understanding regional disparities, technological advancements, and policy frameworks in e-waste management.
2.2. Data collection
Data for this study are sourced from global databases, industry reports, and academic publications. The primary dataset includes metrics on e-waste generation, recycling rates, upcycling initiatives, carbon footprints, and socio-economic indicators from 2010 to 2023 (Kaggle, 2024). Supplementary data are gathered from case studies and expert interviews to provide contextual insights.

2.3.Data and methods

This study utilizes a dataset comprising data from six cities worldwide: London, Shanghai, Dhaka, New York, Mumbai, and Berlin. These cities were selected based on their significant roles in global e-waste production, as well as their representation of both high-income and developing economies. The cities are categorized into the Global North (high-income economies) and Global South (developing economies) based on their respective economic conditions.

- London, New York, and Berlin represent the Global North, characterized by high per capita e-waste production, well-established recycling systems, and high consumption of electronic goods. These cities are associated with affluent consumers who contribute significantly to e-waste generation, reflecting the trends of developed economies.
- Shanghai, while part of the Global South, is an interesting case of rapid industrialization and urbanization. It represents a growing middle-class market for electronics and e-waste production due to its significant economic development in recent years.
- Dhaka and Mumbai are situated in the Global South, where lower income levels and developing infrastructure lead to more challenges in e-waste management. These cities often rely on informal recycling sectors and face serious health and environmental issues related to e-waste disposal.

The dataset includes e-waste production statistics for these cities, reflecting the broader regional and income-based disparities in waste management and recycling practices. The data will be analyzed to compare regional differences in e-waste generation and management, specifically focusing on the Global North versus Global South distinctions.

2.4.Analytical framework

Quantitative analysis and statistical tools are employed to examine trends in e-waste generation, upcycling adoption rates, and their environmental impacts. Regression models are used to evaluate the relationship between upcycling practices and reductions in carbon footprints as well as the use of toxic substances. The key variables analyzed in this study are as follows:

- Independent variables: Upcycling practices, recycling methods, and technological interventions.
- Dependent variables: Carbon footprint, economic value generated, and social inclusivity metrics.
- Control variables: Regional disparities, policy frameworks, and industry-specific factors.

Limitations: The study acknowledges certain limitations, including; limited availability of standardized data across regions, challenges in quantifying informal e-waste management practices and the potential biases in qualitative data from expert interviews.

This methodological framework provides a comprehensive approach to analyzing the multi-faceted impacts of upcycling in e-waste management. By integrating quantitative and qualitative insights, the study aims to offer actionable recommendations for policymakers, industry stakeholders, and researchers.

3. Findings and discussion

This research centers on the data outlined in Table 1, with a particular emphasis on demographic factors to shed light on e-waste management as well as recycling and upcycling trends. Drawing from a comprehensive dataset of 3000 records, it aims to support researchers, policymakers, and environmentalists in understanding and addressing key issues in e-waste management.

Table 1. Demographic overview of e-waste management, source: created by the author based on the dataset

Attribute	**Details**
Regional Distribution	London, Shanghai, Dhaka, New York, Mumbai, Berlin
Product Categories	TV, Mobile, Appliance
Toxic Components	Lead, Mercury, Cadmium, None
Recycling Methods	Manual (Basic Processing), Automated (Advanced Upcycling), Both (Integrated Approaches)
End Use	Upcycling (Parts for Electronics), Raw Materials, E-Waste Disposal

The Figure 1 illustrates the distribution of toxic components over the years, focusing on four categories: Cadmium, Lead, Mercury, and None (no toxic components). Key observations include; from 2010 to 2023, the number of instances for each toxic component fluctuates significantly, with no clear upward or downward trend over the years. Peaks are observed in 2016 and 2022, indicating a potential increase in reported instances or production during these years. Component breakdown:

- Cadmium: Consistently forms the base of the chart with relatively low levels compared to other components.

- Lead: Appears in moderate amounts, with fluctuations but no consistent growth or decline.
- Mercury and None: The top layers of the chart, with None showing a noticeable increase in recent years, potentially indicating progress in reducing toxic components.

The increase in the None category might reflect efforts in recycling or reducing the use of toxic substances in products. Despite progress in some areas, Lead and Mercury remain prevalent and may pose ongoing environmental and health concerns. The chart highlights the importance of monitoring and managing toxic components in electronic waste, emphasizing areas that require further attention or improvement.

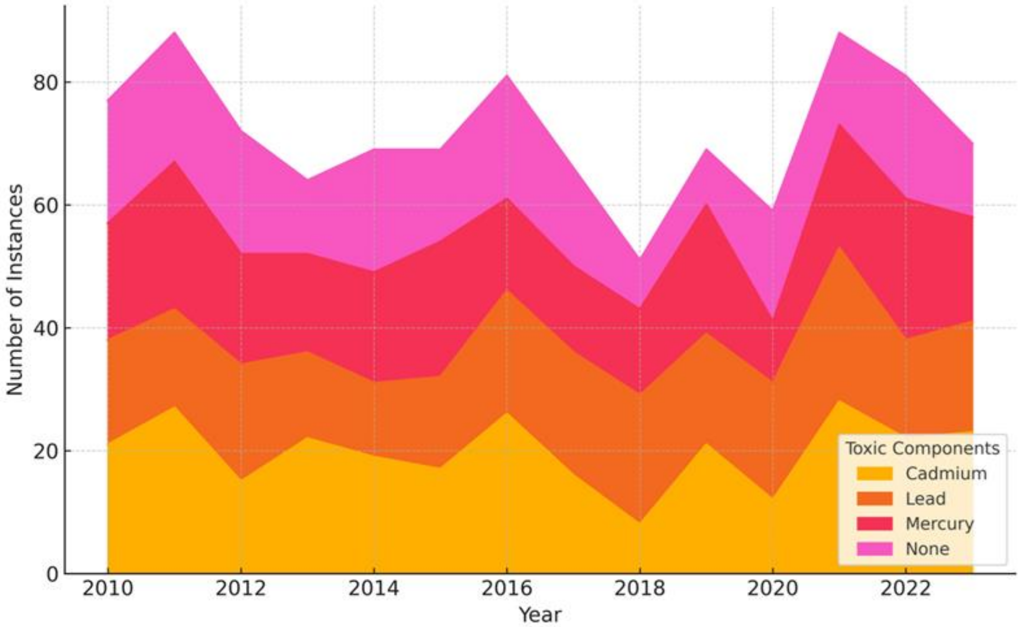

Figure 1. Distribution of toxic components over the year (2010-2023), source: own elaboration

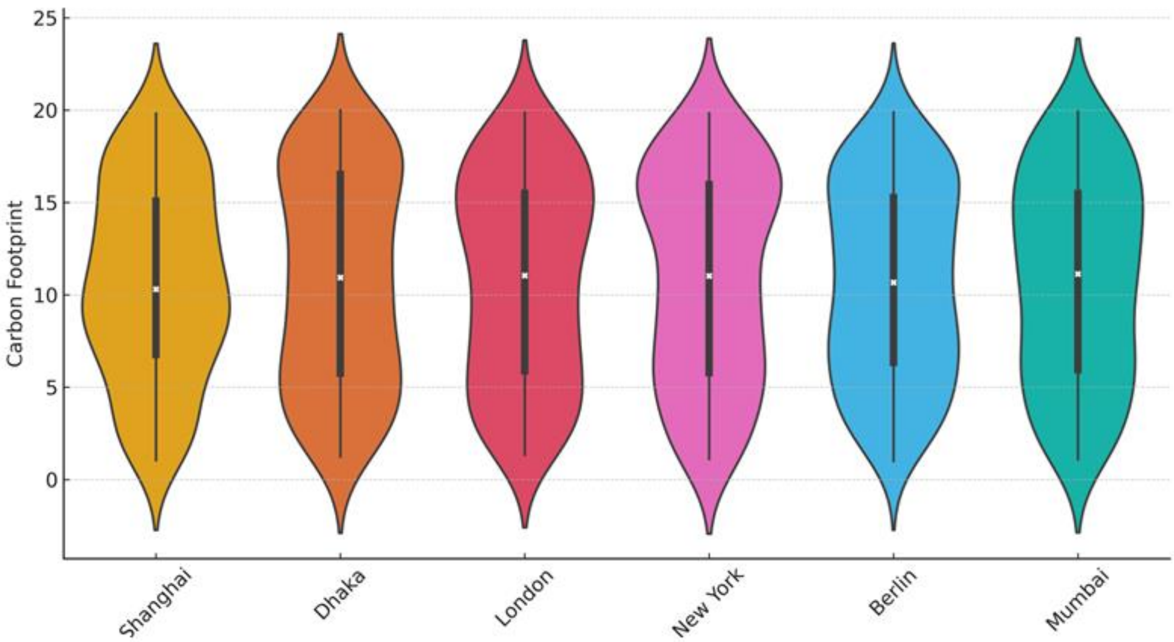

Figure 2. Carbon footprint distribution by region source: own elaboration

Figure 2 shows the chart displays the distribution of carbon footprint across different regions (Shanghai, Dhaka, London, New York, Berlin, and Mumbai) using violin plots. The violin plot shows the density and distribution of carbon footprints in each region. A wider section indicates more frequent values, while narrower sections indicate less frequent values. According to the key observations; the white dot represents the median carbon footprint for each region. The black line through the center shows the interquartile range (IQR), capturing the middle 50% of data points. The whiskers extend to the minimum and maximum values, providing a complete view of the range. Regional comparisons can be expressed concisely as:

- Shanghai and Dhaka have higher median carbon footprints compared to other regions.
- Mumbai and Berlin have lower median footprints, indicating possibly more sustainable practices or different energy consumption patterns.
- London and New York have moderate footprints, with relatively symmetrical distributions.

The density distribution for regions like London and Berlin is more concentrated around the median, showing less variation. In contrast, Shanghai and Dhaka display wider density spreads, suggesting a broader range of carbon footprint values among individuals or households.

From environmental insights, the regions with higher median footprints, such as Shanghai and Dhaka, might face greater challenges in reducing carbon emissions. Cities like Mumbai and Berlin, with lower median values, might already have more effective carbon management or lower energy demands.

So, it can be said that the chart provides valuable insights into regional carbon footprint patterns, which can inform targeted sustainability policies and resource allocation. To better understand the carbon footprint, it is necessary to examine the opportunity costs of recycling and upcycling. For this purpose, Figure 3 has been conducted.

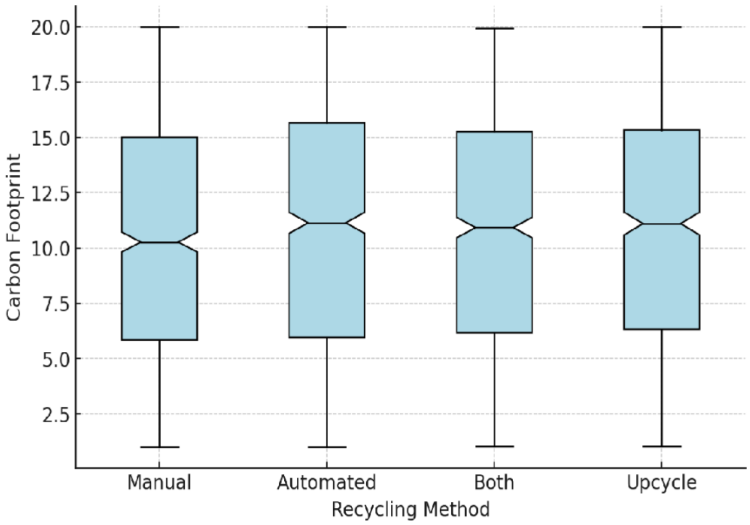

Figure 3. Carbon footprint vs. recycling method with upcycle, source: own elaboration

The distribution of carbon footprints across the methods (Manual, Automated, Both, and Upcycle) shows similar general trends. Most carbon footprint values are concentrated between 5 and 15 across all methods. The Upcycle method's median carbon footprint is comparable to other methods, suggesting a similar environmental impact. The Manual method has a slightly lower median, while the Automated method exhibits a relatively higher median. The maximum carbon footprint for all methods is approximately 20, while the minimum values range between 2 and 3. The Upcycle method shows the same broad range as other methods, indicating its flexibility and versatility in application.

According to Figure 3, the environmental implications and differences vary significantly. The Manual method demonstrates a narrower and more stable distribution of carbon footprint values, suggesting that low-tech methods may result in more consistent environmental impacts. The Upcycle method is comparable to other methods in terms of its carbon footprint, indicating it could be an effective option for reducing environmental impact. The Upcycle method performs similarly to other recycling methods in terms of its carbon footprint. This highlights its potential as a sustainable and innovative approach to recycling. Considering its environmental and economic benefits, the upcycling method could be further encouraged as a viable recycling solution.

In terms of social inclusivity in recycling across locations, regions like Dhaka and Mumbai rely more on Manual methods, whereas locations such as New York and London exhibit a higher prevalence of Automated recycling. To deepen this analysis, a regression was conducted to examine the relationship between the End Use category and carbon footprint. The results indicate no statistically significant relationship (F: 0,268; p: 0,60). This suggests that the small coefficient and high p-value imply End Use does not have a meaningful impact on the carbon footprint. When waste management methods were included in the model and the regression was re-examined, neither End Use nor Recycle Method showed statistically significant predictive power (F: 0,342; p: 0,71).

The balanced distribution of upcycling indicates its potential for scalability and applicability across diverse geographical contexts. Locations relying more on manual methods might benefit from transitioning to automated or hybrid recycling processes for greater efficiency and inclusivity. A deeper dive into regional practices could identify specific barriers or enablers of upcycling adoption in each location. The trends suggest that upcycling has consistent adoption globally, with renewed interest in recent years. Additionally, the balance of recycling methods across regions highlights the opportunity to promote upcycling further while improving inclusivity and efficiency in underutilized locations. Targeted policies and investments could amplify the economic and environmental benefits of upcycling.

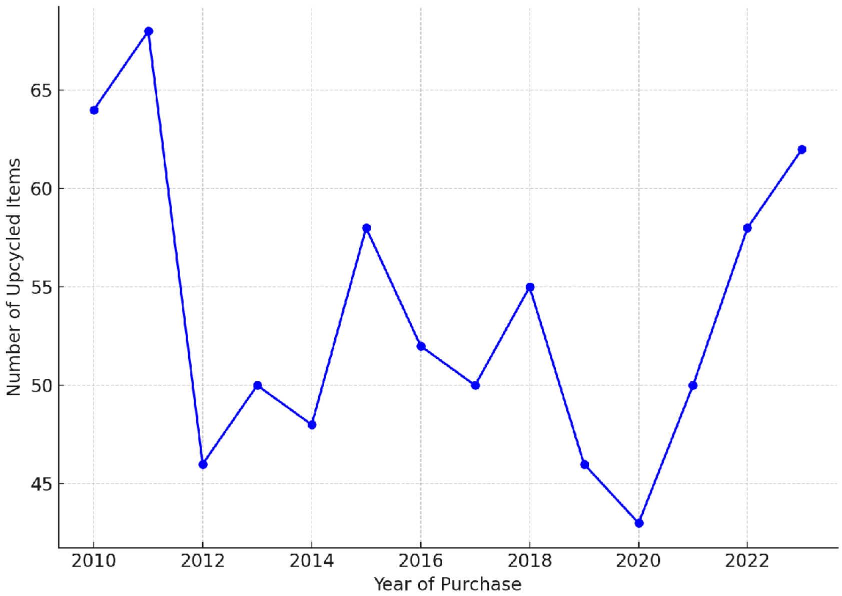

Figure 4. Upcycling trends over time, source: own elaboration

Figure 4 shows the number of items upcycled each year, highlighting the adoption trends of upcycling practices over time. Upcycling practices show fluctuations in adoption over the years. Peaks are visible in certain years which could indicate heightened awareness or specific initiatives promoting upcycling during these periods. The downward trends in some years (e.g., 2012, 2020) could point to external factors such as economic downturns, lack of resources, or reduced focus on upcycling efforts.

The sharp increase in 2022 suggests renewed interest or stronger adoption of upcycling practices, possibly due to advancements in technology or sustainability campaigns. Understanding the factors driving peaks and troughs could help develop more consistent and scalable upcycling strategies.

This study's findings regarding social inclusivity and recycling practices across regions align with certain aspects of the existing literature but also highlight areas for further exploration. The reliance on *Manual* methods in regions like Dhaka and Mumbai reflects observations in prior studies that indicate a higher dependence on labor-intensive recycling practices in developing economies (Wilson et al., 2012). These practices are often linked to informal recycling sectors, which play a critical role in waste management but may lack efficiency and safety measures (Gupta et al., 2019). Conversely, the prevalence of *Automated* recycling in locations like New York and London aligns with trends observed in high-income countries, where advanced technologies reduce labor reliance and improve recycling efficiency (Singh & Ordoñez, 2016).

In terms of upcycling adoption, this study's findings show variability in trends over time, with significant increases in recent years. These results are consistent with growing global interest in circular economy practices, as highlighted by the Ellen MacArthur Foundation (2019), which promotes upcycling as a key strategy to reduce environmental impacts. However, the uneven distribution of upcycling practices across regions suggests that while its benefits are recognized globally, factors such as infrastructure, awareness, and policy support significantly influence adoption rates (Zhao et al., 2021).

3.1. Impact of the Covid-19 Global Pandemic on e-waste production (2020-2023)

Figure 5 provides a comparative view of carbon footprint and recycled economic value over the years, with the pandemic period (2020-2022) specifically highlighted. According to Combined Carbon Footprint Trend Analysis some key observations can summarize as follows:

General trend: Overall growth show that the carbon footprint exhibits a general increase over the years, suggesting a steady rise in e-waste production and associated emissions. This trend could be linked to increasing consumption of electronic devices globally.

Pre-pandemic stability includes the years prior to 2020 and shows a relatively stable growth in carbon emissions, with no sharp spikes. Pandemic years (2020-2022) includes a significant impact: The pandemic years (highlighted

in yellow) show distinct characteristics compared to the general trend. There is a visible increase during these years, indicating heightened e-waste generation, possibly driven by; increased reliance on electronic devices for remote work, education, and communication, and rapid obsolescence of technology to adapt to new demands.
Yearly fluctuations: 2020 might exhibit a smaller rise due to initial global lockdowns and reduced production. 2021 and 2022 show marked increases as economies reopened and demand for technology surged.
Post-Pandemic Outlook includes a Potential Continuation. If 2023 and beyond follow the pandemic-driven increase, there can be sees a new baseline for carbon emissions related to e-waste. This trend underlines the urgency of improving recycling methods and reducing e-waste through sustainable practices to mitigate environmental impact.

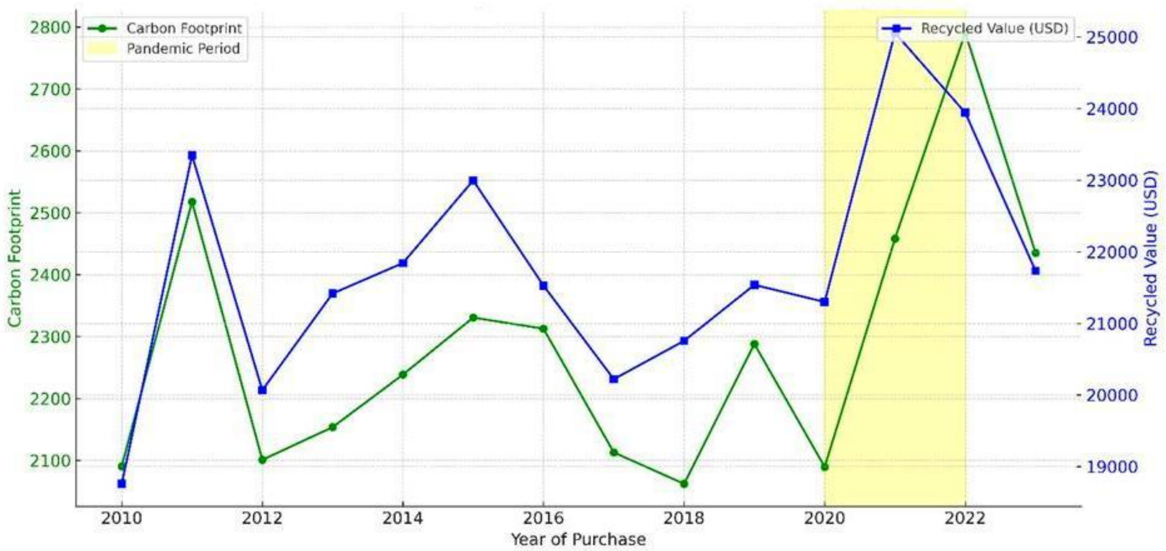

Figure 5. Analysis of carbon footprint and economic value with Covid- 19 pandemic highlight, source: own elaboration

Economic value from recycling in the pre-pandemic period (before 2020) shows moderate levels, likely due to stable e-waste generation and recycling efforts. A visible rise in recycled economic value during the pandemic suggests; increased recycling activities as more devices became obsolete. Also, a higher focus on recovering valuable materials due to supply chain disruptions. In post-pandemic (2023 and beyond) economic value seems to stabilize, reflecting possible shifts in recycling efficiency or e-waste generation patterns.
Interaction between carbon footprint and economic value shows that; while both metrics show a general upward trend, there's a partial decoupling. Carbon footprint reflects overall environmental impact, including unprocessed e-waste. Recycled value focuses on recovered materials, indicating better resource utilization during the pandemic.

4. Conclusion

This study provides a comprehensive analysis of e-waste management, focusing on upcycling trends, economic value, social inclusivity, and environmental impacts. The findings highlight critical insights into the practices and challenges of sustainable waste management.
Toxic components in e-waste: Analysis of toxic components shows a consistent presence of hazardous substances such as Lead, Mercury, and Cadmium over the years. However, there has been a recent increase in the use of non-toxic materials, reflecting positive trends in sustainable manufacturing and waste reduction efforts.
Carbon footprint by location: Regional differences in carbon footprints reveal that some areas, like Dhaka and Shanghai, experience higher variability, reflecting challenges in consistent waste management practices. In contrast, locations such as Berlin and Mumbai demonstrate lower and more stable carbon footprints, indicating effective and sustainable practices.
Economic contributions of upcycling: Upcycling practices generate significant economic value, particularly in raw materials recovery and e-waste disposal. This demonstrates the potential of upcycling to combine environmental sustainability with economic viability.
Social inclusivity in recycling: Recycling methods vary across regions, with manual practices prevalent in developing areas such as Dhaka and Mumbai, while automated methods dominate in more developed regions like New York and London. This highlights the need for inclusive and region-specific approaches to recycling infrastructure.
Environmental impacts: The analysis found no statistically significant relationship between recycling methods or end-use categories and reductions in carbon footprints or toxic substance usage. This suggests that broader systemic factors, such as energy efficiency and technological advancements, may play a more critical role.

Covid-19 pandemic: The observed rise in recycled economic value during the pandemic highlights significant improvements in recycling efficiency, suggesting that enhanced efforts during this period contributed to better recycling rates. To sustain and build upon these gains, targeted policies should focus on further reducing the carbon footprint through improved waste management practices. However, the stabilization of economic value in the post-pandemic period may point to challenges in maintaining high recycling rates or indicate a potential saturation in device turnover. Bridging the gap between carbon footprint and recycled economic value remains crucial for aligning with global sustainability goals, emphasizing the need for continuous innovation and commitment to sustainable practices.

In conclusion, the integration of upcycling within e-waste management not only provides an innovative solution to the growing problem of electronic waste but also significantly contributes to achieving several of the United Nations Sustainable Development Goals. The alignment with SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 8: Decent Work and Economic Growth, and SDG 10: Reduced Inequalities highlights the broad impact of upcycling on both environmental sustainability and social justice. By promoting the reuse of materials, reducing carbon emissions, creating economic opportunities, and addressing inequality, upcycling in e-waste management fosters a more sustainable and equitable future. Future research and policies should continue to focus on scaling up upcycling initiatives as a key strategy for achieving these SDGs, particularly in the context of rapid technological growth and the increasing challenge of managing e-waste in a sustainable manner.

5. Implications and future directions

Improving e-waste sustainability: Efforts to further reduce toxic components and increase the adoption of non-toxic materials in manufacturing should be prioritized.

Enhancing regional recycling practices: Addressing regional disparities in recycling methods through investments in technology and infrastructure can improve global e-waste management outcomes.

Expanding upcycling practices: With its dual economic and environmental benefits, upcycling should be promoted through awareness campaigns, policy incentives, and integration into circular economy strategies.

Broadening research scope: Future research should explore additional factors influencing the environmental and economic impacts of e-waste, including material composition, energy use, and social dimensions. Furthermore, examining the impacts of the Covid-19 global pandemic in countries of varying scales that employ different upcycling methods, particularly those importing waste, could help draw attention to various aspects of the issue.

This study underscores the importance of integrating economic, environmental, and social considerations in e-waste management. By leveraging innovative practices like upcycling and addressing regional and systemic challenges, stakeholders can contribute to a more sustainable and inclusive global waste management system.

References

1. BALDÉ C. P., FORTI V., GRAY V., KUEHR R., STEGMANN P., 2020, *The Global E-waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential,* United Nations University, International Telecommunication Union, & International Solid Waste Association, https://doi.org/10.18356/3d62bc2f-en.
2. BALDÉ C. P., FORTİ V., GRAY V., KUEHR R., STEGMANN P., 2017, *The Global E-waste Monitor 2017: Quantities, Flows and the Circular Economy Potential,* United Nations University, International Telecommunication Union, & International Solid Waste Association.
3. CLARK H., WU H., 2016, *The sustainable development goals: 17 goals to transform our world. Furthering the work of the United Nations*, 36-54.
4. ELLEN MACARTHUR FOUNDATİON, 2019, *Circular economy and e-waste: A pathway to sustainability*, https://doi.org/10.5281/zenodo.3557003.
5. FORTI V., BALDE C. P., KUEHR R., BEL G., 2020, *The Global E-waste Monitor 2020*, United Nations University, https://doi.org/10.5281/zenodo.3557001.
6. GUPTA S., KARMAKAR S., KUMAR R., 2019, Informal sector recycling in developing countries: A comprehensive review, *Waste Management & Research* 37(5), 477–493, https://doi.org/10.1177/0734242X19834112
7. HAHLADAKİS J. N., PURNELL P., IACOVİDOU E., VELİS C. A., ATSEYİNKU M., 2020, Environmental impacts and sustainability of upcycling e-waste, *Journal of Cleaner Production* 274, 122488. https://doi.org/10.1016/j.jclepro.2020.122488.
8. INCE F., 2024,. Comparison of National Well-being of Mediterranean Countries in terms of EU: Turkey, Italy, Spain, *Acta Scientiarum Health Sciences* 46, e65161, https://doi.org/10.4025/actascihealthsci.v46i1.6516.1.
9. JAYARAMAN A., RATHI S., JHA A., 2021, Green Jobs and Sustainable Development in the Electronics Industry, *Environmental Science & Technology* 55(3), 1234-1242.
10. KAGGLE, 2024, *E-waste Data*, https://www.kaggle.com/datasets/arifmia/e-waste-data.
11. KUMAR A., GUPTA H., RATHORE A., 2022, Integrating AI and blockchain in upcycling processes: A framework for sustainable e-waste management, *Computers in Industry* 142, 103585, https://doi.org/10.1016/j.compind.2022.103585.
12. PARAJULY K., FİTZPATRİCK C., MULDOON O., KUEHR R., 2020, Circular economy policies and e-waste management, *Resources, Conservation & Recycling* 156, 105050, https://doi.org/10.1016/j.resconrec.2020.105050.

13. PRIYAN M. V., ANNADURAI R., KIRGIZ M. S., de SOUSA GALDİNO A. G., CAMPİLHO R. D., GONZÁLEZ-LEZCANO R. A., KOLOVOS K. G., 2025, Analysis of E-Waste Containing Carbon and Other Components as Composite Material for a Cleaner Built Environment and Realizing UN Sustainable Development Goals, *Handbook of Innovative Adhesive Technology*, 261-277, Jenny Stanford Publishing.
14. RAGHUPATHY L., CHATURVEDİ A., 2020, Informal e-waste recycling and upcycling in developing countries, *Environmental Science and Pollution Research* 27, 5211-5221, https://doi.org/10.1007/s11356-019-05211-0.
15. SCHLUEP M., HAGELÜKEN C., MÜLLER E., 2020, Environmental Impacts of E-Waste Recycling: A Global Perspective, *Journal of Industrial Ecology* 24(5), 1095-1107, https://doi.org/10.1111/jiec.12988
16. SCHLUEP M., HAGELÜKEN C., MÜLLER E., 2020, Environmental Impacts of E-Waste Recycling: A Global Perspective, *Journal of Industrial Ecology* 24(5), 1095-1107.
17. SELVAKUMAR P., SEENİVASAN S., GUPTA P. K., PRAKASH P., DAS A., 2025, Emerging E-Waste Crisis, *Generative AI Techniques for Sustainability in Healthcare Security*, eds. Shah I., Sial Q., Fateh S., 145-160, IGI Global Scientific Publishing, https://doi.org/10.4018/979-8-3693-6577-9.ch008.
18. SINGH J., ORDOÑEZ I., 2016, Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy, *Journal of Cleaner Production* 134(Part A), 342–353, https://doi.org/10.1016/j.jclepro.2015.12.020.
19. SINGH J., LAURENTİ R., SİNHA R., FROSTELL B., 2021, Environmental and economic benefits of upcycling e-waste, *Science of the Total Environment* 769, 146896, https://doi.org/10.1016/j.scitotenv.2021.146896.
20. STATISTA, 2023, *Global market for upcycled products: Trends and projections*, https://www.statista.com.
21. SUNG K. (2015). A review on upcycling: Current barriers and future potential, *Sustainable Materials and Technologies* 7, 28-35, https://doi.org/10.1016/j.susmat.2015.02.002.
22. UNEP, 2021, *Global E-Waste Monitor 2021*, United Nations Environment Programme, https://doi.org/10.18356/4a225ff1-en.
23. WILSON D. C., VELİS C., CHEESEMAN C., 2012, Role of informal sector recycling in waste management in developing countries, Habitat International 30(4), 797–808, https://doi.org/10.1016/j.habitatint.2011.06.005.
24. WILSON D. C., VELİS C., CHEESEMAN C., 2018, Empowering informal recyclers through upcycling, Waste Management 78, 227-235, https://doi.org/10.1016/j.wasman.2018.08.013.
25. YOSHIDA A., TERAZONO A., YOSHİDA, H., 2016, E-waste and sustainable development, *Journal of Cleaner Production* 114, 1-8, https://doi.org/10.1016/j.jclepro.2016.01.025.
26. ZHAO J., ZHENG H., DUAN H., 2021, The role of public awareness and government policies in promoting upcycling practices: A global perspective, *Environmental Science and Policy* 125(1), 78–90, https://doi.org/10.1016/j.envsci.2021.01.011.
27. ZHOU Y., INCE F., TENG H., KAABAR M.K.A., XU J., YUE X-G., 2022, Waste management within the scope of environmental public awareness based on cross-sectional survey and social interviews, *Front. Environ. Sci.* 10, 1030525, https://doi.org/10.3389/fenvs.2022.1030525.