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(Review Article)

Evaluating the environmental impact of electronics production and the advancement in sustainable manufacturing processes

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Abstract

The electronics industry, despite its technological advancements, faces significant environmental challenges across its lifecycle, from raw material extraction to e-waste disposal, including wastewater pollution, energy consumption, toxic material usage, and greenhouse gas emissions. This critical review highlights the industry's environmental impact, which rivals that of aviation, and explores sustainable manufacturing advancements such as biodegradable materials, green electronics, and energy-efficient technologies. Life Cycle Assessment (LCA) tools are emphasized as essential for evaluating and reducing environmental footprints. The review calls for collaborative efforts among industry leaders, policymakers, and academia to invest in sustainable practices, enforce stricter e-waste regulations, and adopt LCA tools to transition the electronics industry towards more environmentally responsible operations while maintaining its economic and technological significance.

Keywords: Electronics; Manufacture; Sustainability; Production; Environment

1. Introduction

Despite the electronics industry's clean image, the hidden environmental and human costs of electronics manufacturing cannot be overlooked. Over the years, the innovation and development of electrical and electronic equipment have been on a steep rise [1]. Hence, there is a crucial need for the development of various roadmaps to help outline a collaborative, industry-driven strategy to advance sustainable manufacturing, improve competitiveness, and promote environmentally friendly technologies. The environmental impacts associated with a product include those that occur not only at the final stage of assembling parts, but also in the production of parts and their constituent materials [2].

Additionally, most of the footprints for the electronics manufacturing sectors do not come from their Scope 1 emissions, but from the embodied emissions in the supplies of parts, components, chemicals, and materials [3]. The electronics industry faces increasing pressure to measure and reduce its greenhouse gas emissions, as its environmental impact rivals that of the airline industry, necessitating legislation that is likely to mandate carbon footprint assessments for electronic products before they can be sold or used - similar to existing EU requirements for airlines [4]. The integration of sustainability into manufacturing and design is becoming as crucial as traditional metrics like functionality and profitability. Therefore, success in future manufacturing operations will depend on adopting sustainable environmental practices. Ultimately, companies that incorporate sustainability into their design and manufacturing processes are likely to gain a competitive advantage.

The following paper is a critical review to unravel the impacts of electronics production whilst uncovering some advancements in sustainable practices that can help reduce the negative impact of electronic manufacturing processes.

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2. The Strategic Importance and Environmental Challenges of the Electronics Industry

The U.S. government has played a significant role in the development of semiconductor and electronic technologies over the years, thus accounting for about half of worldwide semiconductor sales in 2015 and beyond [5]. The electronics industry is considered strategically vital for economic growth and competitiveness, with its significance largely driven by Moore's Law - a principle established by Intel co-founder Gordon Moore that has guided the industry's rapid advancement for over 25 years [6]. There is no doubt that electronics play a crucial part in various applications, ranging from industrial to domestic use. In this matter, the increasing consumer demand for tech products is generating more e-waste, thus raising concerns about the impact on the environment. Additionally, the convergence of computers, IT, power electronics, and power systems is creating an interdisciplinary technological landscape, exemplified by smart grid development. This integration highlights power electronics' growing strategic importance in national industrial and energy policies worldwide. With the growing demand for electronics, there will always be a growing concern for sustainable approaches.

Some of the key impacts of electronics production are outlined by Ellis [7] in his review titled Environmental issues in electronics manufacturing are outlined below.

- Wastewater Pollution: Electronics manufacturing generates significant wastewater containing heavy metals (e.g., copper, tin, lead), anions (e.g., cyanides, nitrates, sulfates), and organic and halocarbon compounds.
- Energy Consumption: Energy-intensive manufacturing processes, such as drying and hot-air solder levelling (HASL), contribute to global warming and pollution.
- Lead Usage: Lead is a major environmental and health concern, particularly in solder and cathode ray tube production.
- Brominated Fire Retardants: Used in laminates and plastics, these compounds release harmful acids when incinerated or decomposed in landfills.
- Ozone Depletion: Past widespread use of ozone-depleting substances (e.g., CFCs, HCFCs) in cleaning and manufacturing has been reduced in developed countries but persists in developing nations.
- Climate Change: The production and use of fluorocarbons and perfluorocarbons, which have high global warming potential, contribute significantly to greenhouse gas emissions.
- Volatile Organic Compounds (VOCs): Emissions from VOCs used in cleaning, soldering, and coatings contribute to air pollution and smog.
- Public Health Impacts: Pollution from electronics manufacturing, such as respiratory and other chronic diseases, imposes significant health care costs.

These challenges underscore the fact that with the increase of electronics products, their manufacture and disposal are introducing new threats to the fragile balance of the Earth's ecosystems. Nevertheless, electronics can also be the solution to many of our current and future environmental and energy-related problems. This can be achieved by consciously selecting environmentally responsible choices of materials, technology, design, manufacture, distribution, usage, and end-of-life disposal systems [8].

2.1. Sustainable Manufacturing

Modern society depends heavily on manufacturing since it provides essential services and plays a key role in both national and global economies. However, factories and manufacturing plants use up lots of natural resources and create pollution that harms our environment and communities. People now understand that we can't keep using natural resources forever - the Earth has limits. The way we make and use products today puts our future at risk. As a result, manufacturing is changing to focus on three main goals: protecting the environment, supporting the economy, and benefiting society. This new approach aims to make manufacturing more sustainable in the long term [9]. Research from Patil et al. [10] shows that manufacturing companies are being pushed toward sustainability for three main reasons: tighter environmental laws, dwindling natural resources, and growing public concern about environmental issues.

3. Environmental Impact of Electronics Production

Raw material extraction, production processes, and e-waste disposal are some of the major steps for producing electronics. Each step of this process has some substantial impact on the environment and thus needs to be managed sustainably to reduce the environmental footprint.

3.1. Raw Material Extraction

The Environmental consequences of mining and sourcing materials for electronic production cannot be overlooked. For example, the continuous supply of raw materials is integral for the manufacture of electronic components such as semiconductors**,** conductors, and other specialized materials. The environmental impacts of mineral production stages are generally caused by the use of land, energy, water, and chemicals, and the production of waste.

The chart below shows the Global environmental performance of primary production of rare-earth elements in the mining stage between 2010 and 2030.

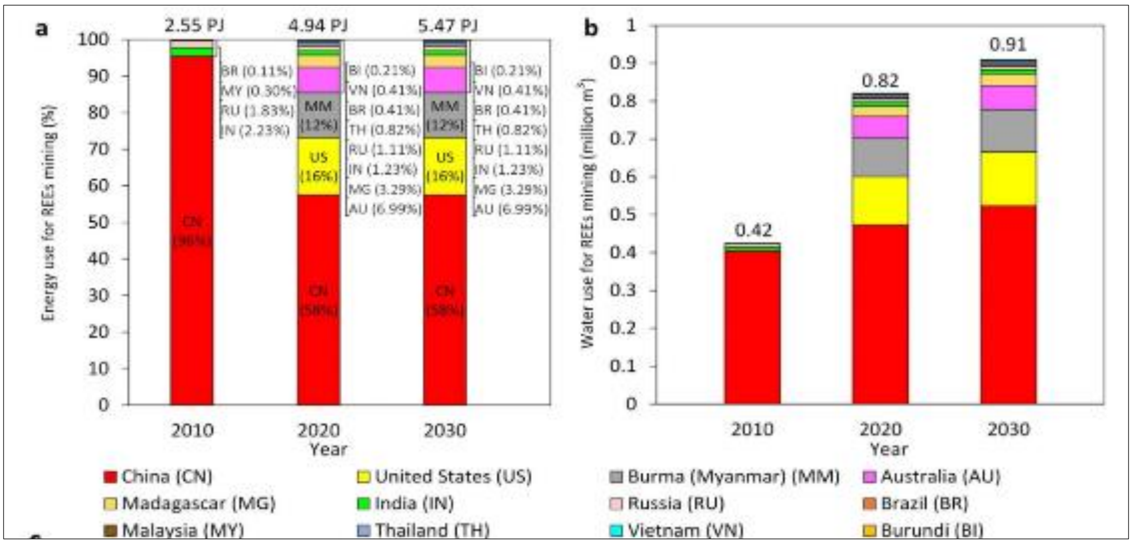

Figure 1 a, Global energy consumption, in petajoules (PJ). b, Global water consumption, in million cubic [8]

In a similar study of two mining sites (Norra Kärr in Sweden and Bayan Obo in China) by Schreiberet. et al [11], the environmental impacts of producing neodymium (Nd) and dysprosium (Dy) were compared. The main environmental concerns at both sites are human toxicity (33-49% of total impacts), aquatic ecotoxicity (22-30%), particulate matter (10-15%), and eutrophication (9-13%). These impacts primarily come from chemical production emissions, heavy metal contamination in water treatment, dust emissions during mining, and phosphoric emissions in waste treatment.

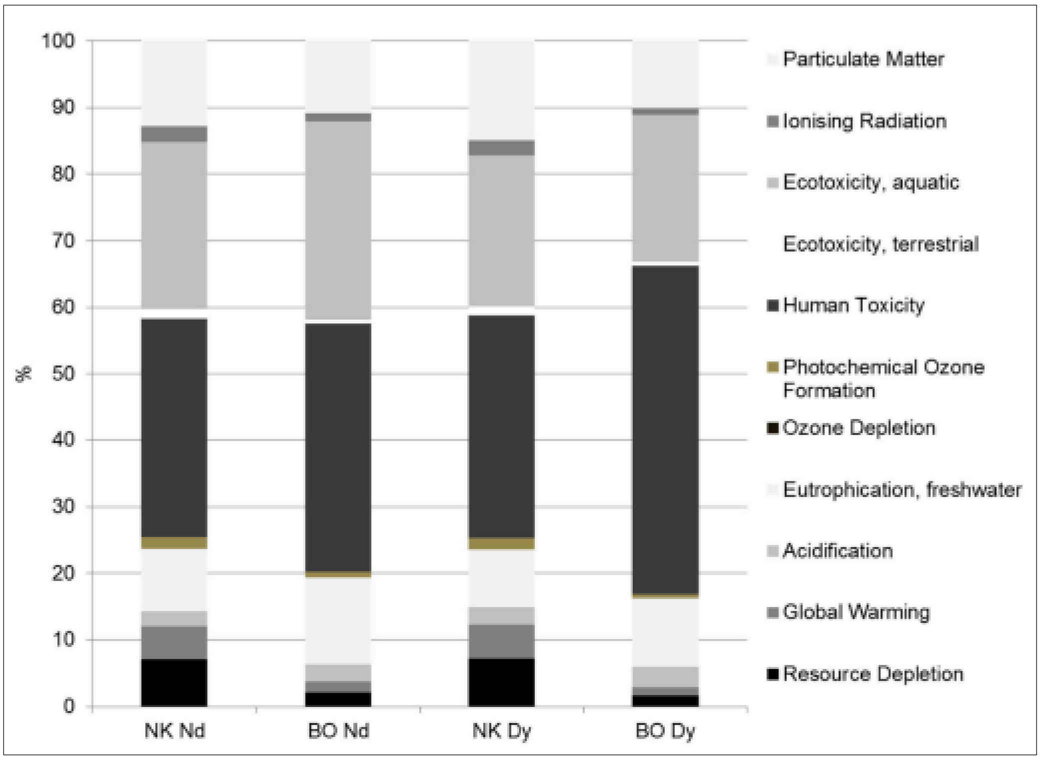

Figure 2 Comparison of relative impacts for the production of 1 kg Nd and Dy at Norra Kärr and Bayan Obo [11]

3.2. Production Processes

In the 2024 publication by Next Generation Mobile Networks Alliance (NGMN-Alliance) [12], the following strategies to limit emissions in the electronic and ICT industry were highlighted

- Companies can reduce emissions by increasing renewable energy usage through solar panels and wind generators on their facilities, which reduces costs and ensures operational continuity.
- Reducing production volume through componentization helps cut emissions, where only rapidly evolving parts are replaced rather than entire units.
- Industry can avoid fossil-based plastics by using recycled plastics (though with some quality trade-offs), biological precursors from plant materials, or ChemCycling, which creates new polymers from decomposed waste plastic.
- Using recycled (secondary) metals instead of primary metals both reduces emissions and can be more cost-effective, particularly for aluminum, which requires only 5% of the energy compared to primary production.
- Hydrogen produced from renewable sources can replace carbon as a reducing agent in technical processes, creating a circular process that only produces water as a byproduct.

3.3. E-Waste and Disposal

Electronic waste consists primarily of computers and mobile phones that are thrown away due to their rapid replacement cycles. Currently, about 20-25 million tons of e-waste are generated annually, with the majority coming from Europe, the US, and Australasia. In the coming decade, China, Eastern Europe, and Latin America are expected to emerge as significant sources of e-waste.

Table 1 Potential Environmental Contaminants Arising from E-waste disposal or recycling [11].

Contaminant	Relationship with E-waste	Typical E -waste concentration (mg/kg)	Annual global emission in E-waste(tons)
Polybrominated diphenyl ethers (PBDE's) polybrominated byphenyls (PBBs) tetrabromobiphenol-A (TBBPA)	Flame retardants		
Polychlorinated biphenyls (PCB)	Condensers, transformers	14	280
Chloroflourocarbon (CFC)	Cooling units, insulation foam		
Polycyclic aromatic hydrocarbons (PAHs)	Product of combustion		
Polyhalogenated aromatic hydrocarbons (PHAHs)	Product of low temperature combustion		
Polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs)	Product of low temperature combustion of PVCs and other plastics		
Americium (Am)	Smoke detectors		
Antimony	Flame retardants, plastics	1,700	34,000
Arsenic (As)	Doping materials for Si		
Barium (Ba)	Getters in cathode ray tubes (CRTs)		
Beryllium (Be)	Silicon-controlled rectifiers		
Cadmium (Cd)	Batteries, toners, plastics	180	3,600
Chromium (Cr)	Data tapes and floppy disks	9900	198,000
Copper (Cu)	Wiring	41,000	820,000
Gallium (Ga)	Semiconductors		
Indium (In)	LCD displays		
Lead (Pb)	Solder, CRTs, batteries	2,900	58,000
Lithium (Li)	Batteries		
Mercury (Hg)	Fluorescent lamps, batteries, switches	0.68	13.6
Nickel (Ni)	Batteries	10,300	206,000
Selenium (Se)	Rectifiers		
Silver (Ag)	Wiring, switches		
Tin (Sn)	Solder, LCD screens	2,400	48,000
Zinc (Zn)		5,100	102,000
Rare earth elements	CRTS screens		

4. Advances in Sustainable Manufacturing Processes

Research by Nihal and Harry demonstrated that innovative electronic technologies, devices, and applications play a significant role in eliminating toxins and pollutants, reducing energy consumption, and enhancing the advancement of solar energy and other renewable energy sources.

One of the innovative solutions highlighted in research by Li et al. [13] in their paper, dubbed Biodegradable Materials and Green Processing for Green Electronics, explored green electronics, which represent a solution to the growing e-waste crisis by adopting the use of biodegradable materials and environmentally friendly manufacturing processes. The paper highlighted the following areas:

- **Materials:** Natural and synthesized biodegradable materials (like cellulose, chitosan, and resins) can be used for substrates, electrodes, and active components
- **Manufacturing:** Focus on low-toxicity materials and solvents in manufacturing, and emphasis placed on cost-effective processes suitable for large-scale production, whilst exploring the need to develop solvent-free, annealing-free, and low-cost manufacturing methods.

The article emphasized that prevention through green electronics is preferable to dealing with pollution, though significant research and development are still needed to make these technologies commercially viable.

Printing technology also offers a promising alternative to traditional Complementary Metal Oxide Semi-Conductors (CMOS) processes for creating biodegradable electronics that can dissolve in liquids. However, achieving fully printed complex systems remains challenging and requires further development of suitable materials and techniques [13]. Wood-derived materials are increasingly attractive as substrates for flexible electronics and optoelectronic devices due to their combination of mechanical flexibility, durability, and favourable optical characteristics [14]. Research also reveals that paper-based electronics offer a sustainable and cost-effective alternative to traditional electronic devices, but despite advantages like biodegradability and flexibility, they still face challenges in performance, durability, and reliability that require further research and development to match conventional sensors [15].

4.1. Energy Efficiency: Strategies for reducing energy consumption during manufacturing.

As highlighted earlier, manufacturing operations have a substantial environmental footprint due to their heavy consumption of diverse resources, including both renewable materials and finite resources like energy, water, and metals [16]. Smart Manufacturing (SM) is gaining momentum across industries as a promising approach that integrates emerging technologies like IoT and robotics to significantly reduce energy consumption compared to traditional manufacturing methods, though it remains in early development stages with opportunities for further advancement through interdisciplinary collaboration [17]. Other strategies, such as Implementing Lean Manufacturing Principles focus on reducing waste in production lines by minimizing defective components, optimizing assembly processes, and employing just-in-time (JIT) manufacturing [18]. Utilizing Energy-Efficient Equipment, such as energy-efficient soldering machines, pick-and-place equipment, and etching tools that are designed to operate with lower power consumption. Such modern energy-efficient equipment reduces the power requirements during assembly and testing processes, where heating and precision equipment consume significant energy. Advances in Mathematics and Computer Science now allow for optimization of electric machine components through multiple aspects, including material distribution and characteristics, alongside traditional electromagnetic analyses and other factors like rotor dynamics and thermal properties [19]. Designing electronics to use fewer raw materials while improving functionality minimizes waste and energy consumption during both manufacturing and recycling phases. Ultimately, conducting routine maintenance prevents energy loss due to inefficient operation, extends equipment life, and avoids unnecessary downtime, which can disrupt energy-efficient workflows in manufacturing processes. By adopting these tailored strategies, electronics manufacturers can reduce their energy consumption, cut operational costs, and contribute to sustainable production practices.

4.2. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) evaluates the complete environmental footprint of a product, tracking potential impacts and resource usage from the initial extraction of raw materials, through manufacturing and usage, all the way to its final disposal or recycling, encompassing every stage from "cradle to grave", including energy consumption, component production, distribution, and end-of-life processing [20].

The article by Laura and Shawn, [21] discusses two main life cycle tools: Compliance X-Sight (CX-S) and Life Cycle Management (LCM) analysis.

CX-S is a web-based application developed by Center Software that helps manufacturers manage, analyze, and report on recyclability and restricted substances in their products. It integrates supplier and customer information with internal bill of materials, tracks supplier reporting, identifies parts containing restricted substances or recycled content, and helps generate documentation for product labels and regulatory compliance. The system uses extensible Markup Language (XML) technology and can collect data throughout the supply chain.

Life Cycle Management (LCM) analysis is a comparative decision-making tool that integrates environmental, health, safety, and recycling (EHSandR) considerations into traditional cost and performance analysis. It's particularly valuable during the product design phase, where it helps identify and compare costs between alternative products or manufacturing processes. LCM helps engineers make decisions that balance economic and environmental factors, encouraging them to consider environmental objectives in product selection. The tool demonstrates that while products containing restricted substances might have lower initial costs, their total life cycle costs could be higher when considering factors like disposal, regulatory compliance, worker safety requirements, and recycling.

In research that compares the environmental impacts of two contrasting consumer electronics - a high-value smartwatch and a low-value TV remote – the findings reveal that different strategies are needed to reduce the environmental impacts in the product lifecycle based on their components. For the smartwatch, the main environmental burden comes from producing its sophisticated integrated circuits (ICs), suggesting that extending device lifespan and improving IC recycling are key. In contrast, the TV remote's environmental impact primarily stems from its fiberglass (FR4) circuit board material rather than its simpler ICs, indicating that using eco-friendly materials and manufacturing methods would be more effective for reducing the environmental impact of simpler, lower-cost electronic devices (Zhang et al., 2024).

4.3. Corporate and Policy Initiatives

To combat global E-waste disposal, it is also important to promote comprehensive policy frameworks, Extended Producer Responsibility, and Waste Electrical and Electronic Equipment (WEEE directives) alongside advocating for improved public awareness, proper disposal methods, and incentivized recycling programs [22]. Electronic waste is the fastest-growing category of hazardous solid waste in the world. Addressing the problem will therefore require international collaboration, economic incentives that protect labor, and management approaches that minimize adverse impacts on the environment and human health [23].

5. Conclusion

This review has revealed that the electronics industry faces significant environmental challenges across its entire value chain, from raw material extraction to e-waste disposal. The industry's environmental impact rivals that of aviation, with major concerns including wastewater pollution, energy consumption, toxic material usage, and greenhouse gas emissions. However, promising advances in sustainable manufacturing are emerging, including green electronics using biodegradable materials, smart manufacturing technologies, and improved energy efficiency strategies. Life Cycle Assessment (LCA) tools have become crucial in evaluating and reducing environmental impacts, while corporate initiatives and policy frameworks are gradually shifting toward more sustainable practices.

Several gaps in current knowledge and practices remain unaddressed. First, while biodegradable electronics show promise, they still face significant challenges in matching the performance and durability of conventional devices. Second, the implementation of sustainable manufacturing processes often encounters economic barriers, particularly in developing countries where environmental regulations may be less stringent. Third, despite advances in e-waste management, the recycling rate remains critically low at only 16% of generated waste.

Recommendations

The urgency for transitioning to sustainable electronics production cannot be overstated. We recommend the following collaborative actions

- Industry leaders should prioritize investment in research and development of green electronics and sustainable manufacturing processes, particularly focusing on bridging the performance gap between conventional and biodegradable materials.
- Policymakers must develop and enforce stronger regulations around e-waste management and establish standardized frameworks for measuring environmental impacts across the electronics industry.
- Academia should focus research efforts on developing cost-effective sustainable technologies and materials that can be scaled for commercial production.
- Manufacturers should adopt comprehensive Life Cycle Assessment tools to evaluate and optimize their environmental impact from design through disposal.
- Cross-sector collaboration between academia, industry, and government agencies should be strengthened to share knowledge, resources, and best practices in sustainable electronics manufacturing.

These actions, implemented collectively, can help transform the electronics industry into a more environmentally responsible sector while maintaining its crucial role in technological advancement and economic growth.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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