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Threats of Internet-of-Thing on Environmental Sustainability by E-Waste

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Abstract: Human activities are at the heart of interactions between physical and digital spheres enabled by the Internet and the proliferation of Internet-of-Things (IoT) devices destined to be discarded. The rejected devices, called e-waste, contain toxic substances that negatively impact environmental sustainability. There are no studies to examine the impacts of the Internet and IoT on the sheer volume of e-waste, which is the objective of this paper. Based on an extensive literature review, two propositions were advanced, and three secondary datasets were used to test the propositions from 2000 to 2021. The first dataset relates to the world Internet penetration through variables associated with network accessibility. The second dataset is linked to the global proliferation of the IoT through its technological functionality. The third dataset is the worldwide volume of e-waste measured in millions of metric tons. Our findings indicate that the Internet and the IoT play pivotal roles in the e-waste crisis. Network accessibility and technological functionality significantly and positively influence the variability in the volume of e-waste, thus threatening environmental sustainability. Several actionable recommendations encourage developers, politicians, policymakers, and users of electronic devices to pay closer attention to the escalating size of e-waste threatening environmental sustainability.

Keywords: e-waste; the Internet; Internet-of-Things

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1. Introduction

The dawn of the 21st century saw the proliferation of the Internet and an upsurge in the Internet-of-Things (IoT) to integrate intelligence and control operation functions through the delicate crafting of electronic devices. Between 2000 and 2021, Internet users increased from 413 million to 4.95 billion, while Internet-connected devices grew from a compelling notion to 46 billion installed worldwide [1–3].

1.1. Problem Statements

The sheer volume of devices paralleled the growing mass of discarded electronic products called e-waste. With an annual increase of 2.5 million tons (M.T.) or a 187% rise since the turn of the new millennium, the World Health Organization [4] considers e-waste a serious threat to the world economy, its ecosystems, and human health. In 2021, for example, the world generated 57.4 MT of e-waste worth US $62.5 billion, of which less than 20%, or US $10 billion in value, was recycled [5]. The remainder was either lost, buried in landfills, or found its way to less-developed nations, where they were poorly managed and badly recycled [4]. For e-waste, the present recycling process involves dismantling, shredding, and acid-washing in the open air, where toxic dust particles permeate and gases float into the air and seep into the soil and the water table, causing irreparable damage to the environment and people's health [6].

Furthermore, the escalating demand for electronic devices has tripled manufacturing since 1970. This has required mineral processing that adversely affects the environment through land alteration causing deforestation, biodiversity loss, and water and soil contamination. This process also triggers the alteration of soil profiles, causing erosion and the formation of sinkholes [7,8].

1.2. Objective

Researchers have listed several factors contributing to that escalating volume of e-waste over the past four decades. Still, the impacts of the Internet and the IoT on e-waste remain unexamined. Although this topic may be contentious, such a study can provide insights into the work of three groups overlooking the e-waste that is presently circling civilization for the kill. These groups include those who consider themselves pioneers of the founders of the Internet and the IoT; politicians who are screaming their brains out for digital transformation; and hyperconnected societies living in a Cloud-cuckoo-land paradigm, addicted to the dopamine that their Internet-connected devices release.

This study proceeds in three sections: a literature review on e-waste, its contributing factors, and the IoT, a methodology that highlights the contextual framework for this study, followed by a summary and actionable recommendations.

2. Literature Review

2.1. E-Waste

Gao et al. [9] conducted an extensive bibliometric analysis of the e-waste literature published between 1981 and 2018. They listed 571 journals that published 2800 articles written by 6573 scholars. Their analysis shows a lack of a standard definition for e-waste. Sakar [10] provides the most concomitant definition, which refers to e-waste as electronic devices destined to be discarded after exhausting their primary utility values. The U.S. Environmental Protection Agency also defines e-waste as discarded electronic products reaching the end of their useful lives through redundancy or breakage. The most concomitant definition is provided by Widmer et al. [11], and Forti et al. [12], who refers to e-waste as electronic devices destined to be discarded after exhausting their primary utility values. The European Union Waste Electronic and Electrical Equipment Directive [13], Grant et al. [14], and Man et al. [15] add rejected electrical products to the definition. The Australian Bureau of Statistics [16] considers e-waste unwanted electric and electronic equipment powered by electric currents or electromagnetic field functions, including components, subassemblies, and consumables. The Basel Convention [17] extends the European definition of e-waste by considering all discarded electrical and electronic products that contain hazardous materials with adverse impacts on human health and the environment.

These discrepancies in the definition of e-waste coupled with overlapping terminologies have resulted in diverse classifications of e-waste. The United States Environmental Protection Agency [18] classifies e-waste into ten groups arranged by weight, size, function, and end-of-life attributes. They include large and small household appliances, IT equipment, consumer electronics, lamps and luminaires, toys/leisure products, tools, medical devices, monitoring and control instruments, and automatic dispensers [10,19]. Balde et al. [20] group e-waste into six categories: small household machines, large household appliances, temperature exchange equipment, screens and monitors, communication and information technology devices, and consumer products. Still, recycled e-waste includes five groups: home appliances, communication and information technology devices, home entertainment, electronic utilities, office equipment, and medical devices. The discrepancies in these classifications are reflected in the inaccuracies in the collection, storage, transboundary reports, and data collection about e-waste.

The existing data, based on the European definition, reveals a rapid increase in e-waste from 20 MT in 2000 to 57.4 MT in 2021, of which Asia generates 24.9 MT, followed by the Americas (13.1 MT), Europe (12 M.T.), Africa (2.9 MT), and Oceania (0.7 MT). According to the International Telecommunication Union [2] and Singh [3], by 2030, e-waste will be the fastest-growing solid waste stream globally, exceeding 74.7 million tons yearly. The World Bank [21] predicts that by 2050, global E-waste will double to more than 111.00 MT in volume each year, causing environmental degradation and jeopardizing human health and well-being.

2.2. Contributing Factors

Researchers list numerous factors contributing to the staggering volume of e-waste (see Table 1) as the appetite for electronic devices increases, along with their development, use, spread, and discard.

Table 1. Contributing Factors to E-Waste.

An Increasing Trend in the World's Population and Urbanization	[20]
Rising global GDP per capita leads to increased spending on electronics	[4]
Growing dependencies on digital systems by government, private, and individuals	[22]
Digitalization of civilization for political, economic, and social dominations	[23]
Digital migration for remote work and increasing adoption of digital platforms	[24]
The popularity of non-fungible tokens is driven by cryptocurrency	[8]
Planned hardware/software design obsolescence	[25]
Institutionalization of advanced technologies as a benchmark for literacy	[25]
Rapid technological changes in network technologies-from 3G to 4 and 5G	[26]
Infrastructure to enable technological changes	[27]
Growing disposal of appliances to replace the new ones (e.g., Artificial Intelligence)	[27]
Accelerated raw material discovery and developments	[28]
Growing awareness of environmentally friendly products	[2]
Spatial, political, socio-cultural, and economic	[3]
Low volume of recycling for discarded electronic products	[18]

However, the impacts of the Internet and the IoT on e-waste remain unnoticed. At the same time, the United States National Intelligence Council [29] notes that the IoT-based Internet is crucial in managing key functions in its systems activations, action specifications, communications and security, and its detection of support-specific goals. According to this report, the highest level of cruciality is a paradigm shift leading civilization away from fossil fuels. The goal is to have pervasive and entrenched Internet nodes reside in every "Thing" for automatic detection, tracking, segmentation, classification, and behavior-analysis surveillance for geopolitical, military, economic, and social cohesion. Thus, the Internet penetration and IoT applications for the individual and the residential, industrial, public, and private sectors will escalate.

2.3. The Internet-of-Things

The IoT bridges the physical and digital world, resting on the worldwide interconnection of public and private networks that use the standard Internet protocol suite (TCP/IP). It is a network of physical devices embedded with technologies connected to the Internet that work together for data interoperability [25,30,31]. According to the International Telecommunication Union report [2], the IoT is an infrastructure designed for hyperconnected societies that are facilitated by information and communication technologies to create an ecosystem that connects the Earth's four subsystems: the lithosphere (land), hydrosphere (water), biosphere (living things), and atmosphere (air). The principle behind this infrastructure is to unify the Earth's subsystems on a common platform to gain insights into operations by expanding and utilizing real-time self-reporting devices for interaction, collaboration, remote tracking, manipulation, and control.

Cisco [1] reports that IoT applications extend from governments to individuals and public and private industries, with 23.8 billion devices in 2021. It is estimated that by 2025, the number of global Internet-connected devices will reach 40.2 billion, of which 30.8 billion will have an unlimited geographical scope, depending on their intelligence.

2.4. IoT Architecture

IoT intelligence varies based on its architecture. Mashal et al. [32] present a basic three-layer architecture (Figure 1), including perception, network, and application. The perception layer comprises heterogeneous things that are embedded with five components: 1. radio-frequency identification (RFID) tags that uniquely identify things that are used for tracking and controlling by browsing an Internet address or database entry corresponding to a particular RFID or near-field communication technology [19]; 2. sensors to collect real-time data; 3. actuators to trigger a change in surroundings; 4. processors that monitor and send data to communications chips to be stored and processed; and 5. transceivers that convert electrical signals to optical (light) and then back to electrical signals for sending and receiving data [27].

The network layer is the bridging element responsible for connecting an array of IoT gateways to the Cloud platform through a traditional TCP/IP network. Since networks are often partitioned into subnetworks and connect to other networks for wide-area communications, specialized hosts called gateways, middleware, or routers forward packets between networks. These gateways act as bridges between multiple devices and facilitate network connectivity by sending data to the proper application location(s) or the Cloud. A typical IoT communication process is carried out using devices that send these communications directly from sensors to the Cloud or through gates that provide appropriate data ports (input/output) for communication purposes.

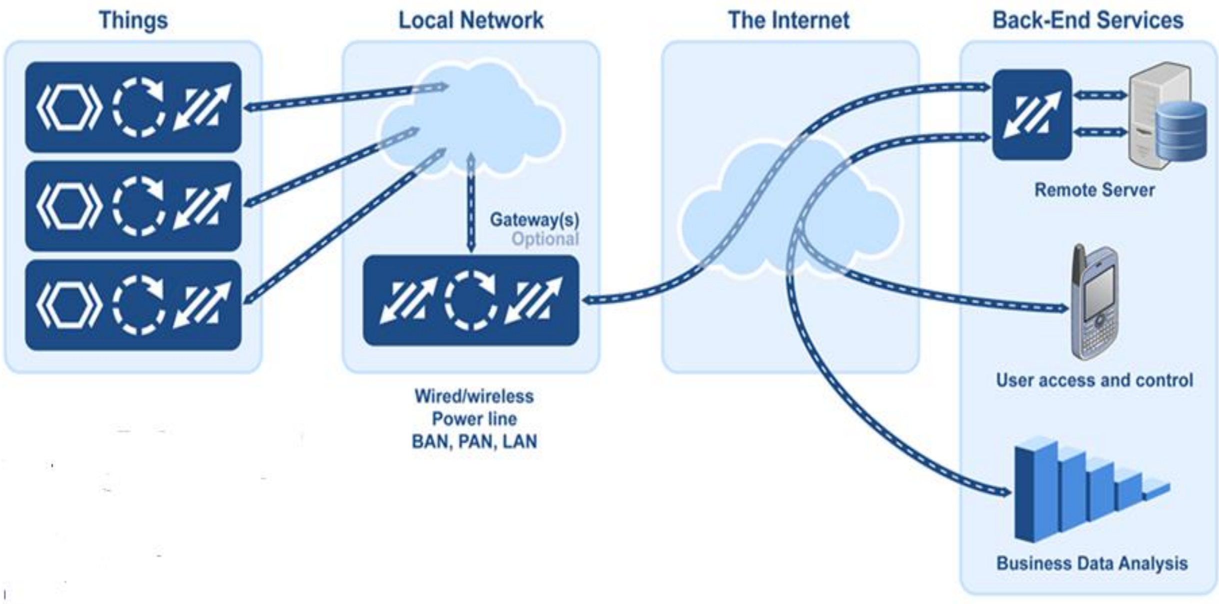

Figure 1. A Three-Layer IoT Architecture: perception, network, and application. Source: Ref. [32].

The application layer interfaces between heterogeneous devices and the network handling the data formatting and delivering the application-specific services to users. These applications synthesize the data for the end-user to derive meaningful insights. Ning and Wang [33] note that the development of these IoT devices is inspired by human intelligence and the ability to think, feel, remember, make decisions, and react to the physical environment. These authors also propose a system that is a three-layer architecture containing three parts: a data center that represents the brain as it processes and manages data; a distributed network of data-processing nodes and smart gateways, signifying the spinal cord; and networking components and sensors, signifying a network of nerves or a nervous system.

The IoT is the logical leap toward ubiquitous Cloud-based computing that adds smart functionality to ordinary objects. Many network protocols facilitate capturing, communicating, transmitting, and processing massive amounts of data to the Cloud or other devices in coordination with the application layer. The most common communication technologies for short-range low-power communication protocols include RFID, near-field communication, Bluetooth, Zigbee, and Wi-Fi for the medium range. The Cloud is a vast global network of remote servers hooked together with software and databases on servers. These servers are meant to operate as a single ecosystem. They are designed to store and manage data, run applications, or deliver content or services such as streaming videos, webmail, operating office productivity software, or providing access to social media functionality (Figure 2).

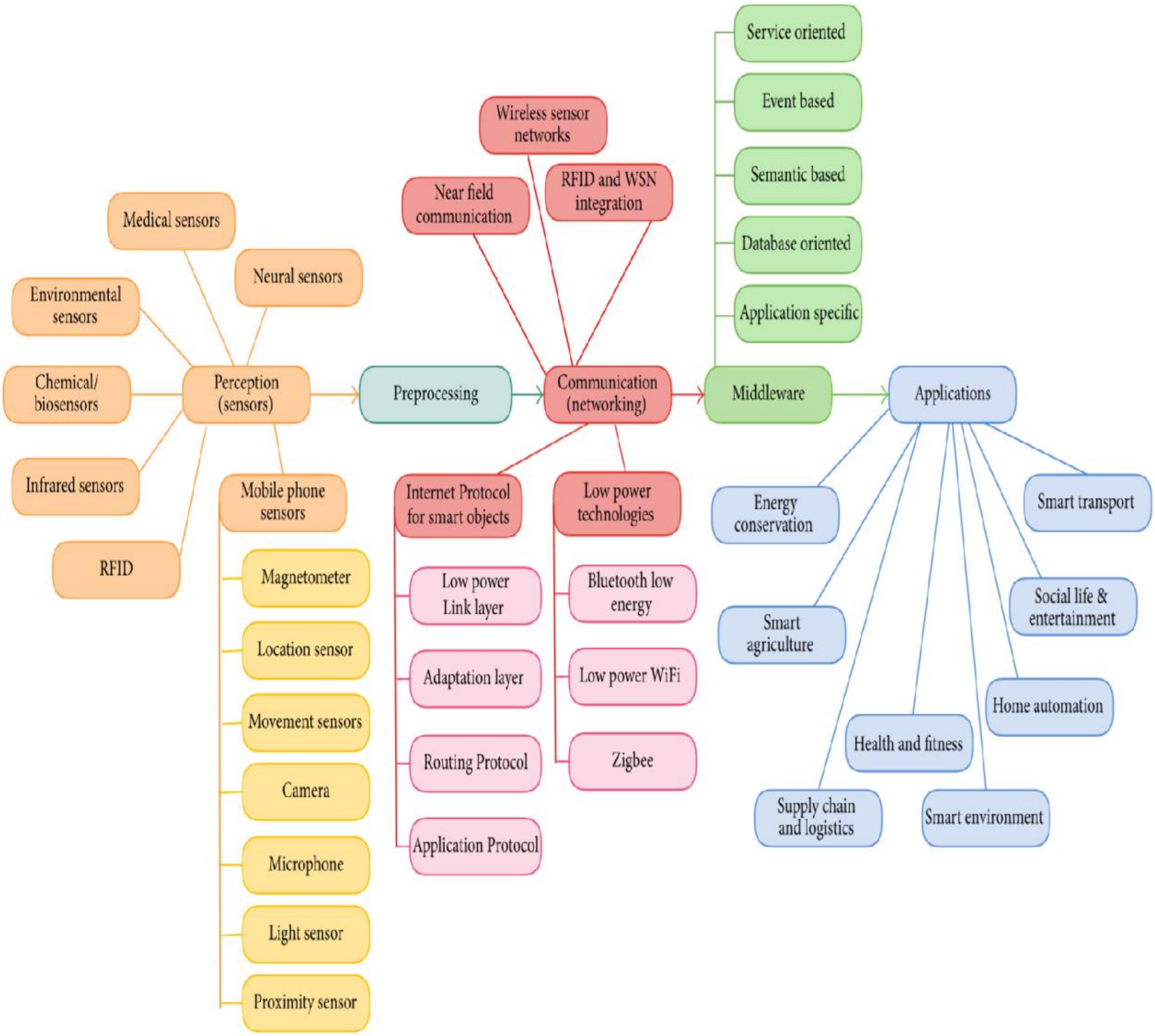

Figure 2. A Five-Layer Internet-of-Things Architecture. Reprinted from [27].

2.5. Five-Layer Architecture

Pallavi and Smruti [32] and Weyrich and Ebert [34] describe a five-layer architecture that is used for more complex applications (see Figure 2). This architecture has transport and processing layers built on its primary three-layer architecture. The transport layer transfers the sensors' data from the perception to the processing layer and vice versa through networks. The processing layer, known as the middleware, stores, analyzes and processes the data it receives from the transport layer.

2.5.1. Cloud-Based Architecture

Due to the extensive data on the Internet, Cloud-centric architecture is used as a storage center on Internet servers instead of hard drives on personal computers. The Cloud is a large, centralized storage space between applications and networks [22]. The Cloud provides efficient flexibility and scalability and offers a core infrastructure and platform, software storage, data mining, machine learning, and visualization tools. However, it cannot solve the increasing demands of real-time or latency-sensitive applications, especially with its bandwidth limitations. Therefore, a new computing paradigm, known as Fog-Computing architecture, has been offered to complement Cloud computing. Fog-Computing extends the Cloud services to the edge of the network. It facilitates computation, communications, and storage closer to these edge devices and end-users, enhancing the low-latency, mobility, network bandwidth, security, and privacy users expect from the Cloud. The Fog layer resides between the perception layer (sensors and devices) and the transportation layer (gateway) in what might be called the local network for a particular IoT cluster.

Edge-Computing is a closely related architecture to Fog-Computing. Its goal is to process information closer to the user and lighten the load of the entire network for all users. It also supports new applications with lower latency requirements while processing data more efficiently to save network costs and increase data-processing security. Thus, this architecture shifts computing resources closer to users' devices from central data centers and Clouds. In some cases, the Fog- and Edge-Computing architectures can be hybridized with Cloud-centric architecture. Edge-Computing can extend to Mist-Computing, where data is processed at the farthest edge of the Cloud. As a subclass of Fog-Computing, Mist-Computing architecture attempts to optimize scalable, cost-efficient platforms, distribute data analytics, allocate limited resources, and reduce response times.

In brief, the IoT signifies connecting heterogeneous devices to create a network capable of making real-time computations through Edge-Computing/Mist-Computing and receiving information to and from the Cloud.

2.5.2. IoT Hardware

A stream of electronic hardware, mostly short life-cycle components, is continuously created, used, and discarded, depending on the IoT level of the architecture. The hardware generally includes sensors, actuators, resistors, capacitors, transducers, diodes, transistors, inductors, integrated circuits, microcontrollers, transformers, batteries, fuses, relays, switches, motors, and circuit breakers. The IoT network uses short- and mid-range coverage technologies with wireless connections, such as ZigBee, Bluetooth, and Z-Wave. Technologies for long ranges are based on 4G and 5G systems operating alongside each other. The network connection requires physical cables to access the Internet (i.e., copper telephone wires, TV cables, and fiber optic cables) through wireless connections such as wireless fidelity (Wi-Fi). The networking equipment includes macro and micro antennas, towers, and in-building systems that connect mobile users and wireless devices to the main core network (the mobile exchanges and the data networks that manage these connections). Optical fiber-based networks facilitate longer distances between users, devices, apps, and the Internet.

The IoT hardware generally contains metals, such as beryllium, brominated flame retardants, cadmium, chromium, lead, mercury, gold, silver, palladium, platinum, copper, lithium, nickel, zinc, aluminum, and tin, all of which are essential in the manufacturing of electronics infrastructure and data centers. Non-metal materials include clays, glasses, plastics, rubber, petroleum-based materials, and carbon. Semimetal materials such as silicon, antimony, arsenic, germanium, polonium, bismuth, cobalt, fluorite, garnet, magnesium, and talc are used in microchips, and semiconductors use tin, graphite, and alkaline [35].

The European Union Waste Electronic and Electrical Equipment Directive (2022) identifies IoT wastes with high risks to human health as those containing beryllium, brominated flame retardants, cadmium, lead, zinc, chromium, mercury, and nickel. Researchers verify the adverse effects these substances have on human health as they are associated with cancers of the lung, skin, and bladder [36]. Others report accumulating cadmium compounds in human kidneys, genitourinary systems (tubular dysfunction), central and peripheral nervous systems, fetuses, and reproductive systems [26].

Further, mining processes and tailings spills are damaging the ecosystem, thereby increasing the uptake of IoT technology and doubling the demand for the Earth's metals over the past two decades. Experts estimate a 250% increase in rare-earth resource extraction by 2030. For example, one metric ton of circuit boards contains up to 800 times the amount of gold and 40 times the amount of copper that is usually extracted from one metric ton of mined ore; or an 80 g smartphone consisting of 20% iron, 14% aluminum, and 7% copper leaves; overall, they estimate 44,400 g of mine tailings spills, and mining the metals required for one computer leaves tailings spills of around one ton. (The United States Environmental Protection Agency [18].)

In brief, a review of the literature that examines the impacts of the IoT on global e-waste conceptually interlocks a collection of views from multiple disciplines organized in three areas: the Internet, the IoT, and e-waste, which lack a standard definition for e-waste, hindering its classification and causing discrepancies in the reported data and its trend.

3. Methodology

There is no scientific consensus in the literature for this study to make predictive hypotheses. However, two propositions were advanced to provide a framework for testable procedures:

Proposition 1. *The Internet positively influences the variability in the volume of e-waste.*

Proposition 2. *The Internet-of-Things positively influences the variability in the volume of e-waste*.

To determine a methodology pertinent to the above propositions, this study used Creswell [24], Tashakkori, and Teddlie [28]. They recommend using objective measurements and descriptive statistical analysis to understand the relationships between the Internet, the IoT, and e-waste. This method requires quantitative data collection to allow the analysis and interpretation to support or refute the stated propositions.

3.1. Data Collection

The propositions were tested using three sets of secondary data from 2000 to 2021 (Figure 3). These sources include International Telecommunication Union [2], Our World in Data [37], and the World Bank [21]. The first dataset facilitates assessments of the impacts of the Internet as measured by network accessibility; the second dataset is related to how the IoT is influenced by technological functionality; the third measures the volume of global e-waste. Network accessibility is measured using five variables: the percentage of world internet users to the total world population, the number of world mobile subscriptions, individual Internet subscriptions, fixed broadband subscriptions (any high-speed data transmission to a residence or a business that transports multiple signals and traffic types), and IoT-connected devices. The IoT functionality is measured using four variables: the number of secure-internet servers per one million people, the number of floating points carried per second (i.e., in real numbers that contain decimals), the number of transistors that can fit into a microprocessor (the more transistors that can fit on a chip, the faster and more efficient the processor is), and the IP traffic, that is, the flow of data across the entire Internet. The global volume of e-waste is measured in millions of metric tons based on the European definition of e-waste by considering all discarded electrical and electronic products that contain hazardous materials with adverse impacts on human health and the environment.

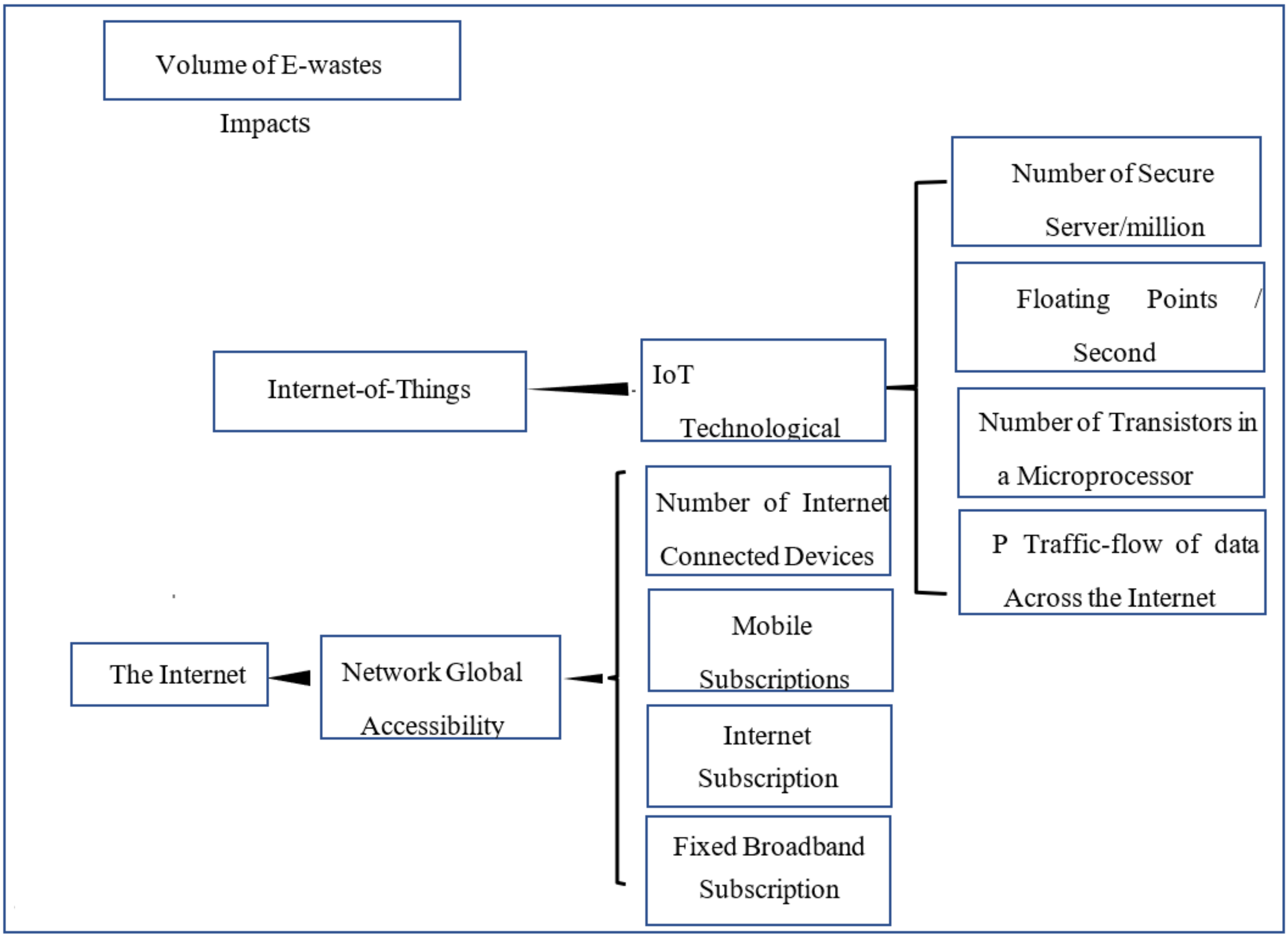

Figure 3. Collected Data for Assessing Impacts of the Internet and Internet-of-Things on E-waste, 2000 to 2021. Source Refs. [2,21,37].

3.2. Data Analysis

The quantitative data analysis was divided into two steps to test the propositions:

Step 1. Testing Proposition One: The Internet positively influences the variability in the volume of e-waste.

In this step, a correlation matrix was used to determine the linear relationship (correlation coefficient) between variables associated with Internet accessibility and e-waste. As presented in Table 2, the interrelationships between variables related to internet accessibility and the relationship between the volume of e-waste and the percentage of the world's internet users (r—0.95) and mobile subscriptions (r—0.94), and the number of Internet-connected devices (r = 0.91), fixed broadband subscriptions (r = 0.95), and individual Internet Subscriptions (r—0.78) were all found to be positive and significant. Therefore, these variables were used in a multiple regression analysis to examine their impact on e-waste.

Table 2. Correlation Matrix for Testing Proposition One.

Variables	World Internet	Mobile Subscriptions	Individual Internet Subscriptions	Number of Connected Devices	Fixed Broadband Subscriptions	E-Waste Metric Tons
World Internet users	1					
Mobile Subscriptions	0.975	1				
Individual Internet Subscriptions	0.839	0.873	1			
Number of Connected Devices	0.959	0.885	0.737	1		
Fixed Broadband Subscription	0.993	0.974	0.836	0.966	1	
E-waste-Metric Tons	0.960	0.948	0.784	0.910	0.954	1

In testing Proposition One, our hypothesis is an association between the Internet and e-waste. The statistical model used to predict the value of e-waste as the dependent variable is based on the variables related to Internet accessibility as the independent variables and is as follows:

$$Y = \alpha + aX1 + bX2 + cX3 + dX4 + eX5 + \text{error term}$$

where

Y = e-waste, α = constant value,

X1 = percentage of the world's Internet users,

X2 = number of world mobile subscriptions,

X3 = number of individual Internet subscriptions,

X4 = number of Internet-connected devices,

X5 = number of fixed broadband subscriptions.

The summary outcome of the multiple regression model presented in Table 3 shows that the multiple R = 0.966, which is an absolute value of the correlation coefficient signifying a strong positive linear relationship between the Internet independent variables (X1 to X4) and the dependent variable (e-waste). Furthermore, the coefficients of determination, the R square = 0.933, and the adjusted R = 0.92, explain the strong influence of the variables associated with the Internet on the variation in e-waste, referring to the high precision of the model.

Table 3. Step 2—Summary Output Testing Proposition One.

Regression Statistics						
Multiple R	0.96629					
R Square	0.93772					
Adjusted R Square	0.92098					
Standard Error	4.45863					
Observations	32					
ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*	
Regression	5	7281.95	1456.39	73.26		
Residual	26	516.86	19.87			
Total	31	7798.81				
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*
Intercept	15.95	1.43	11.09	2.31	13.01	18.91
Internet users	0.31	0.76	−0.41	0.04	−1.89	1.25
Mobile Subscriptions	1.24	7.76	1.6	0.01	−3.52	2.84
Internet Subscriptions	1.09	1.18	−0.92	0.03	−3.53	1.34
Connected Devices	2.88	2.13	1.34	0.18	−1.15	7.29
Fixed Broadband Subscriptions	0.1	0.07	−1.36	0.02	−0.25	0.05

Variance (ANOVA) analysis demonstrates the statistical significance of the independent variables (Internet accessibility) with a 95% confidence level. Still, there is a 5% risk that no association exists when there is, in fact, an actual association. The variables associated with Internet accessibility significantly influence e-waste. *The significance of F*, or the probability that the regression model is wrong, is almost zero. Therefore, Proposition One is accepted, and the prediction model for this proposition is Y = 15.9 + 0.3X1 + 1.2X2 + 1.09X3 + 2.8X4 + 0.1X5.

Step 2. Testing Proposition Two: The Internet-of-Things positively influences the variability of e-waste.

In this step, a correlation matrix was used to examine the linear relationship between the variables associated with the functionality of the IoT and the volume of e-waste. As presented in Table 4, the relationship between the volume of e-waste and the number of secure Internet servers is positive and moderate (r = 0.56). Still, the relationship between e-waste and the global IP traffic (r = 0.84), the number of transistors in the microprocessor (r = 0.70), and the number of floating points carried per second (r = 0.95) are all positive and significant. Therefore, the variables associated with the IoT were used to test Proposition Two in a multiple regression analysis.

Table 4. Step 3, Correlation Matrix for Testing Proposition Two.

	Ewaste-Million Tone	**Internet Server/ Million People**	**Global IP Traffic**	**# Of Transistors In Microphone**	**Floating Point Carried/Second**
Ewaste-Million tone	1				
Internet server/ Million People	0.570	1			
Global IP Traffic	0.845	0.793	1		
# Of Transistors in Microphone	0.707	0.954	0.928	1	
Floating point Carried/second	0.975	0.522	0.522	0.672	1

In testing Proposition Two, the hypothesis is that the IoT significantly influences the variability of e-waste. The statistical model used to predict the value of e-waste as a dependent variable is based on the variables related to the IoT functionality as the independent variables.

The linear prediction model is Y = α + aX1 + bX2 + cX3 + dX4 + error term, where Y: e-waste,

α = Constant value

a = Coefficient for X1: Number of secure Internet servers per one million people,

b = Coefficient for X2: Global IP traffic,

c = Coefficient for X3: Number of transistors in microprocessors,

d = Coefficient for X4: Floating points carried per second.

Table 5 presents the summary outcome of the multiple regression analysis. In this table, multiple R = 0.97 is the absolute value of the correlation coefficient, representing a strong positive linear relationship between the independent variables (X1 to X4) and the dependent variable (e-waste). The coefficient of determination R^2 = 0.95 and the adjusted R = 0.95 explain the strong influence of the variables associated with the IoT on e-waste variation, referring to the high precision of the model.

Table 5. Summary Output, Testing Proposition Two.

Regression Statistics							
Multiple R	0.979						
R Square	0.958						
Adjusted R Square	0.952						
Standard Error	3.379						
Observations	32						
ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*		
Regression	4	6988.54	1747.14	153.05	0.00		
Residual	27	308.22	11.42				
Total	31	7296.77					
Variables	*Coefficients*	*Standard Error*	*t Stat*	*p-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	35.259	5.467	−6.450	6.526	−46.476	−24.042	−46.476
Internet Server/Million People	0.623	0.001	1.019	0.317	−0.001	0.002	−0.001
Global IP Traffic	0.000	0.0000397	0.999	0.327	−0.0000418	0.0001	−0.0000418
# of transistors in Microp.	0.000	0.0000549	−0.835	0.411	0.000	0.0000668	−0.0002
Floating point Carried/second	0.005	0.0005	10.766	2.84×10^{-11}	0.004	0.006	0.004

The statistical analysis of the variance (ANOVA) as part of the multiple regression output used to test Proposition Two demonstrates the statistical significance of the independent variables (IoT functionality). The variables associated with the IoT significantly influence e-waste with a 95% confidence; that is, the regression model provides a good fit for testing Proposition Two. *The significance of F*, or the probability that the regression model is wrong, is almost zero. Therefore, Proposition Two is accepted.

Building on the ANOVA, the following model predicts the value of e-waste as a dependent variable versus the variables related to the functionality of the IoT as the independent variables:

$$Y = \alpha + aX1 + bX2 + cX3 + dX4$$

4. Discussion and Summary

In the 21st century, the Internet and IoT devices offer flexibility, agility, and affordability of accessible information via Internet-connected devices. These technological advances have inexorably changed civilization on Earth, but they have also magnified the volume of e-waste, posing serious threats to environmental sustainability and human health.

Based on an extensive literature review, two propositions were advanced to provide a framework for testable procedures: Proposition One—the Internet positively influences the variability in the volume of e-waste; and Proposition Two—the Internet-of-Things positively influences the variability of the volume of e-waste. These two propositions relate to the Internet infrastructure along several dimensions, such as scale, performance, accessibility, and functionality, which have materialized in the IoT and are largely attributable to satisfying basic industrial and community needs. Utilizing electronic devices effectively pushes the internet infrastructure forward for the proliferation and commercialization of the Internet. Thus, the Internet has become a commodity service with the attention on using it as a global information infrastructure to support commercial and non-commercial services. However, it has also escalated environmental challenges through discarded IoT devices called e-waste.

Three secondary datasets are used to test the propositions from 2000 to 2021. The first dataset relates to the Internet penetration through network accessibility measured by five variables, based on the European e-waste definition recommended by the International Telecommunication Union (2): the percentage of the world's internet users and the numbers of world mobile, individual Internet, fixed broadband subscriptions, and Internet-connected devices. The second dataset relates to the proliferation of the IoT through technological functionality as measured by four variables: the number of secure internet servers per one million people, floating points carried per second, transistors that can fit into a microprocessor, and the Internet protocol (IP) traffic. The third dataset is the global volume of e-waste measured in millions of metric tons.

A correlation matrix and multiple regression analysis were used to justify a methodology pertinent to the study's two propositions to examine the impacts of the Internet and the IoT on environmental sustainability through e-waste. The analysis reveals that network accessibility influences the variability in the volume of e-waste positively and significantly. Further statistical analysis revealed that the variables associated with the IoT significantly influence e-waste with a 95% confidence; that is, the regression model provides a good fit for testing Proposition Two. *The significance of F*, or the probability that the regression model is wrong, is almost zero. Therefore, Proposition Two is accepted.

Thus, both propositions were accepted, and the Internet and IoT impact environmental sustainability through e-waste.

5. Recommendations

This study offers several actionable recommendations for authorities, developers, policymakers, and users of electronic products. First, there should be a standard definition for e-waste, coupled with a unified classification for accurate reporting on the volume, the types of materials, and the transboundary flows of discarded electrical and electronic products. Second, data related to e-waste composition should be provided; it should include the costs of collecting, warehousing, and recycling e-waste and transportation to its final destination. Third, to create a trade code for exporting used products and a tracking system to enable accurate reporting on exports and re-export flows. Fourth, legislation over global e-waste and its disposal should be strengthened. Fifth, recycling should be increased to 100% of discarded electronic products. Sixth, there should be a transition from a linear economy to a circular one by eliminating waste during a design process that outlines the five stages of extraction, production, distribution, consumption, and disposal through a calculated process. At the same time, efforts should be made to keep all materials and components at their highest value. Thus, the functionalism of intellectual roots should be used to design and implement strategies for waste pollution prevention, life-cycle analysis, eco-efficiency assessments, and materials flow analysis. Finally, devices should be re-evaluated, repaired, and reused. One should donate them to social programs or deliver them to formal recycling organizations and find a device that offers multiple functions if they are beyond repair.

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References

1. Cisco Annual Internet Report 2018–2023. White Paper. 2020. Available online: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html (accessed on 13 June 2022).
2. International Telecommunication Union. Global E-Waste Monitor. 2020. Available online: https://www.itu.int/en/ITU-D/Environment/Pages/Spotlight/Global-Ewaste-Monitor-2020.aspx (accessed on 13 June 2022).
3. Sinha, S. State of IoT 2021: Number of Connected IoT Devices Growing 9% to Billion Globally, Cellular IoT Now Surpassing 2 Billion. 2021. Available online: https://iotanalytics.com/number-connected-iotdevices/ (accessed on 13 June 2022).
4. World Health Organization. Soaring E-Waste Affects the Health of Millions of Children. 2021. Available online: https://www.who.int/news/item/15-06-2021-soaring-e-waste-affects-the-health-of-millions-of-children-who-warns (accessed on 13 June 2022).
5. Bhutada, G. All the Metals We Mine Each Year, in One Visualization. World Economic Forum. 2021. Available online: https://www.weforum.org/agenda/2021/10/all-tonnes-metals-ores-mined-in-one-year/ (accessed on 13 June 2022).
6. Cucchiella, F.; D'Adamo, I.; Koh, L.; Rosa, P. Recycling of WEEEs: An Economic Assessment of Present and Future E-Waste Streams. 2015. Available online: https://eprints.whiterose.ac.uk/89119/ (accessed on 13 June 2022).
7. Dudka, S.; Adriano, C. Environmental Impacts of Metal Ore Mining and Processing: A Review. *J. Environ. Qual.* **1977**, *26*, 590–602. Available online: https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq1997.00472425002600030003x (accessed on 13 June 2022). [CrossRef]
8. Warhate, S.; Yenkie, M.; Caudhari, M.; Pokale, W. Impacts of Mining Activities on Water and Soil. *J. Environ. Sci. Eng.* **2006**, *8*, 81–90. Available online: https://pubmed.ncbi.nlm.nih.gov/17913182/ (accessed on 13 June 2022).
9. Gao, Y.; Ge, L.; Shi, S.; Sun, Y.; Liu, M.; Wang, B.; Shang, y.; Wu, J.; Tian, J. Global Trends and Future Prospects of E-Waste Research: A Bibliometric Analysis. *Environ. Sci. Pollut. Res. Int.* **2019**, *26*, 17809–17820. Available online: https://pubmed.ncbi.nlm.nih.gov/31037528/ (accessed on 13 June 2022). [CrossRef] [PubMed]
10. Sakar, A. Dad Brought Home Lead, Kids Got Sick. 2016. Available online: https://www.cincinnati.com/story/news/2016/02/12/dad-brought-home-lead-kids-got-sick/80078164/ (accessed on 13 June 2022).
11. Widmer, R.; Oswald-Krapf, H.; Sinha-Khetriwal, D.; Schnellmann, M.; Boni, H. Global Perspectives on e-waste. *Environ. Impact Rev.* **2005**, *25*, 436–458. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0195925505000466 (accessed on 13 June 2022). [CrossRef]
12. Forti, V.; Baldé, K.; Kuehr, R. E-Waste Statistics: Guidelines on Classifications, Reporting and Indicators. 2018. Available online: http://collections.unu.edu/view/UNU:6477 (accessed on 13 June 2022).

13. The European Union Waste Electronic and Electrical Equipment Directive-2012/19/E.U. 2012. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN (accessed on 13 June 2022).
14. Grant, K.; Goldizen, C.; Sly, D.; Brune, N.; Neira, M.; van den Berg, M.; Norman, E. Health Consequences of Exposure to E-Waste: A Systematic Review. *Lancet Glob. Health* **2013**, *1*, e350–e361. Available online: https://www.thelancet.com/journals/langlo/article/PIIS2214-109X(13)7010,1-3/fulltext (accessed on 13 June 2022). [CrossRef]
15. Man, M.; Naidu, R.; Wong, H. Persistent Toxic Substances Released from Uncontrolled E-Waste Recycling and Actions for the Future. *Sci. Total Environ.* **2013**, *463*, 1133–1137. Available online: https://pubmed.ncbi.nlm.nih.gov/22840636/ (accessed on 13 June 2022). [CrossRef] [PubMed]
16. The Australian Bureau of Statistics. Waste Account, Australia, Experimental Estimates. 2013. Available online: https://www.abs.gov.au/ (accessed on 13 June 2022).
17. The Basel Convention. Controlling Transboundary Movements of Hazardous Wastes and their Disposals. 2002. Available online: http://www.basel.int/TheConvention/Overview/Milestones/tabid/2270/Default.aspx (accessed on 13 June 2022).
18. The United States Environmental Protection Agency. Cleaning up Electronic Waste (E-Waste). 2019. Available online: https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste (accessed on 13 June 2022).
19. Wang, F.; Huisman, J.; Meskers, C.; Schluep, M.; Stevels, A.; Hagelüken, C. The Best-of-2-Worlds Philosophy: Developing Local Dismantling and Global Infrastructure Network for Sustainable E-Waste Treatment in Emerging Economies. *J. Waste Manag.* **2012**, *32*, 2134–2146. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0956053X12001407?via%3Dihub (accessed on 13 June 2022). [CrossRef] [PubMed]
20. Baldé, P.; Forti, V.; Gray, V.; Kuehr, R.; Stegmann, P. The Global E-Waste Monitor 2017: Quantities, Flows and Research. 2017. Available online: https://scholar.google.com/citations?view_op=view_citation&hl=en&user=jSt2ChIAAAAJ&citation_for_view=jSt2ChIAAAAJ:isC4tDSrTZIC (accessed on 13 June 2022).
21. The World Bank Global Waste to Grow by 70 Percent by 2050 Unless Urgent Action Is Taken: World Bank Report. 2018. Available online: https://www.worldbank.org/en/news/press-release/2018/09/20/global-waste-to-grow-by-70-percent-by-2050-unless-urgent-action-is-taken-world-bank-report (accessed on 13 June 2022).
22. Gangwar, H.; Date, H.; Ramaswamy, R. Developing a Cloud-computing adoption framework. Global Business Review. *Glob. Bus. Rev.* **2015**, *16*, 632–651. Available online: https://journals.sagepub.com/doi/abs/10.1177/0972150915581108 (accessed on 13 June 2022). [CrossRef]
23. Shree, D.; Singh, R.K.; Paul, J.; Hao, A.; Xu, S. Digital platforms for business-to-business markets: A systematic review and future research agenda. *J. Bus. Res.* **2021**, *137*, 354–365. [CrossRef]
24. Creswell, J. *Planning, Conducting, and Evaluating Quantitative and Qualitative Approaches to Research. Educational Research*; Prentice Hall: Hoboken, NJ, USA, 2002; Available online: https://www.scirp.org/(S(351jmbntvnsjt1aadkozje))/reference/reference.aspx?referenceid=2667303 (accessed on 13 June 2022).
25. Peña-López, I. ITU Internet Report 2005: The Internet Things. 2005. Available online: https://ictlogy.net/bibliography/reports/projects.php?idp=501 (accessed on 13 June 2022).
26. Ackah, M. Informal E-Waste Recycling in Developing Countries: Review of Metal (loid)s Pollution, Environmental Impacts and Transport Pathways. *Environ. Sci. Pollut. Res.* **2017**, *24*, 24092–24101. [CrossRef] [PubMed]
27. Pallavi, S.; Smruti, S. Internet of Things: Architectures, Protocols, and Applications. *J. Electr. Comput. Eng.* **2017**, *2017*, 9324035. Available online: https://downloads.hindawi.com/journals/jece/2017/9324035.pdf (accessed on 13 June 2022).
28. Tashakkori, A.; Teddlie, C. *Mixed Methodology: Combining Qualitative and Quantitative Approaches*; Sage Publications: Thousand Oaks, CA, USA, 1998; Volume 46, Available online: https://www.scirp.org/(S(i43dyn45teexjx455qlt3d2q))/reference/ReferencesPapers.aspx?ReferenceID=1507633 (accessed on 13 June 2022).
29. The United States National Intelligence Council 2009. Available online: https://irp.fas.org/nic/ (accessed on 13 June 2022).
30. Gope, P.; Hwang, T. BSN-Care: A secure IoT-based Modern Healthcare System Using Body Sensor Network. *IEEE Sens. J.* **2016**, *16*, 1368–1376. Available online: https://ieeexplore.ieee.org/document/7332745 (accessed on 13 June 2022). [CrossRef]
31. Vermesan, O.; Friess, P.; Guillemin, P.; Gusmeroli, S.; Sundmaeker, H.; Bassi, A.; Jubert, I.S.; Mazura, M.; Harrison, M.; Eisenhauer, M.; et al. Internet of Things Strategic Research Roadmap. *Internet Things-Glob. Technol. Soc. Trends* **2011**, *1*, 9–52. Available online: https://www.researchgate.net/publication/267566519_Internet_of_Things_Strategic_ResearchRoadmap (accessed on 13 June 2022).
32. Mashal, I.; Alsaryrah, O.; Chung, T.; Yang, C.; Kuo, W.; Agrawal, A. Choices for Interaction with Things on Internet and underlying Issues. *Ad Hoc Networks* **2015**, *28*, 68–90. [CrossRef]
33. Ning, H.; Wang, Z. Future Internet of Things Architecture: Like Mankind Neural System or Social Organization Framework? *IEEE Commun. Lett.* **2011**, *15*, 461–463. Available online: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C48&q=29.%09Ning%2C%2BH.%2C%2BWang%2C%20%2BZ.%2B%2B%282011%29.%2BFuture%2Binternet%2Bof%2Bthings%2Barchitecture%3A%2Blike%2Bmankind%2Bneural%2Bsystem%2Bor%2B%09social%2Borganization%2Bframework&btnG (accessed on 13 June 2022). [CrossRef]
34. Weyrich, M.; Ebert, C. Reference Architectures for the Internet of Things. *IEEE Softw.* **2016**, *33*, 112–116. Available online: https://ieeexplore.ieee.org/document/7367994/authors#authors (accessed on 13 June 2022). [CrossRef]

35. Yeap, G. Smart Mobile SoCs Driving the Semiconductor industry: Technology Trend, Challenges and Opportunities. In Proceedings of the 2013 IEEE International Electron Devices Meeting, Washington, DC, USA, 9–11 December 2013; Available online: https://ieeexplore.ieee.org/abstract/document/6724540 (accessed on 13 June 2022).
36. Frazzoli, C.; Orisakwe, E.; Dragone, R.; Mantovani, A. Diagnostic Health Risk Assessment of Electronic Waste on the General Population in Developing Countries' Scenarios. *Environ. Impact Assess. Rev.* **2010**, *30*, 388–399. Available online: https://www.osti.gov/biblio/21499136-diagnostic-health-risk-assessment-electronic-waste-general-population-developing-countries-scenarios (accessed on 13 June 2022). [CrossRef]
37. Our World in Data 2022. Available online: https://ourworldindata.org/ (accessed on 13 June 2022).