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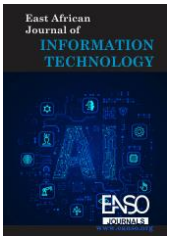

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Original Article

A Review of Current Research Trends in Green Computing

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ABSTRACT

Green computing also called green ICT refers to any computing process or practice aimed at reducing any negative effect that computing technology has on the environment. Technology is ever-advancing hence new technological devices are being developed that could have varied effects on the environment. This study aims at assessing different fields of green computing. The most recent studies were considered from the world's most revered scientific journal IEEE. Countries where the research was carried out were also compared as well as the year when the studies were published. Analysis was done in the different thematic areas where current and future research trends in those areas were discussed. Insightful information from the study was used to do a projection of future research in this area. This study pointed out areas where adjustments or improvements need to be made to ensure green computing is achieved.

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INTRODUCTION

Green computing refers to any computing practice or activity whose aim is to reduce the impact of technology on the environment while ensuring sustainability (Baroudi, Hill, Reinhold, & Senxian, 2009). Green computing covers any process aimed at optimizing energy consumption in developing, using, and managing systems, chips, networks, and software, ensuring they do not negatively impact the environment (Sojoodi, 2021). Research in green computers covers an

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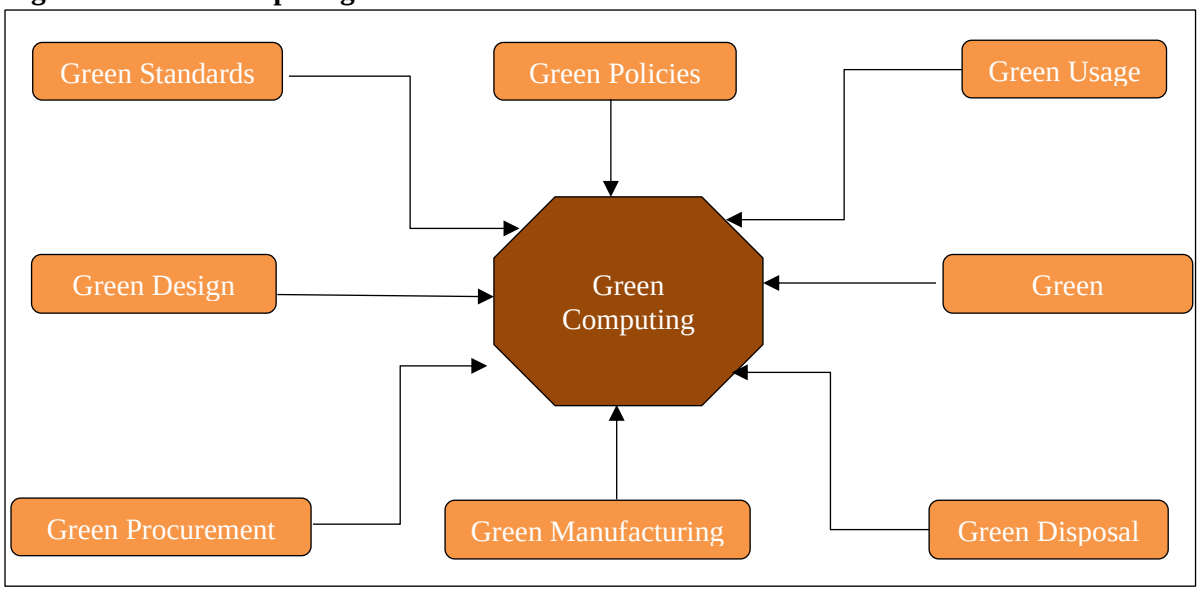
array of sections including the design, development, deployment, use and disposal of e-waste in a more environmentally friendly way. Since the inception of computers in the mid-20th century, there has been increased usage of computing devices ranging from computers, servers, and mobile devices among others. The term green computing was coined in the 1990s and since then it has increasingly gained popularity as the world is becoming more concerned with the environment and how ICT affects it (Kushwaha, 2023). There are approximately 15.14 billion connected devices, which are projected to increase to 29.42 billion in 2030 (Vailshery, 2023). This means that more carbon emissions will be released by such devices, which have a big potential to increase global warming and deplete the earth resources.

Green computing has mixed impacts on society. On the positive side, green computing reduces energy consumption, hence enhancing environmental sustainability. Reduced energy consumption also lowers operational costs. Designing computing systems for green computing calls for sophisticated designs that ensure systems are as efficient as possible. Such systems are more dependable. However, extra resources may be required for such designs, increasing the cost of developing and designing green computing-compliant systems. The disposal and management of e-waste remains a challenge that has not been fully solved and may need extra resources and concerted efforts to be achieved (Mor, Sangwan, Singh, Singh, & Kharub, 2021).

European Union denotes that ICT contributes around 3.9% of total carbon emissions an increase from earlier 2.1% in 2022 (Rolling Plan for ICT standardisation, 2023). This increase clearly shows the need for concerted efforts to work towards and try to reverse this impact. With such worrying rising trends, it is therefore important for humanity to make concerted efforts towards the adoption of environmentally friendly activities as we keep on harnessing the benefits of technology. To achieve the goals of green computing, the world must formulate and adopt the necessary strategies that can drive this ambitious goal. Green standards and policies must be developed to guide the development and use of these computing strategies (Nwankwo, Akinola, & Ukhurebor, 2020). Organizations must consider green design, development, manufacturing, usage, and disposal of all computing equipment (Kaur & Kaur, 2019).

This study aims at establishing research trends in green computing pinning out areas that are of high interest to researchers. With such findings, future researchers will easily identify areas that they should focus on in a bid to solve this complex problem of global warming.

Figure 1: Green Computing



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LITERATURE REVIEW

Since the 1990s when the term green computing was coined, it has over time gained popularity attracting more research and investment in this area. Much research has been carried out to investigate and analyse different research trends in green computing. Therefore, this research will review previous and current research trends in this area to identify gaps and propose areas of future research.

Initial research in green computing focused on putting a lot of emphasis on re-designing computing systems to make them more energy efficient, thus reducing carbon emissions to the environment (Saha, 2018). Current trends have included re-engineering, coordination, and optimization of manufacturing processes, supply chain, and any other workflow of the organization to reduce their impact on the environment.

A study conducted by Wabwoba et. al., in 2019 assessing the readiness of developing countries to adopt and implement green computing noted that apart from the commonly used Molla's G-model to assess the readiness of organizations to adopt green computing, it was necessary to assess the readiness of the IT personnel as well (Wabwoba, Wanyembi, Omuterema, & Omieno, 2013). Hence, including this in the G-model as the 6th variable will be crucial as organizations in developing countries move towards adopting green computing technologies. With Molla's G-readiness model, it does not include personnel, especially the IT ones as key players in the adoption of green computing, yet they play a central role. Kenya being a developing country was found to have low green ICT awareness as compared to other countries like the USA, Australia, and New Zealand.

ICT personnel play a central role in the implementation of green computing within organizations (Wabwoba et al., 2013). There is very low readiness of ICT personnel to adopt green computing due to a lack of necessary training and professional development (Wabwoba, Mbugua, Ikoha, & Shisoka, 2014). With such findings, organizations and governments can now invest in ICT personnel ensuring they have the necessary understanding of green computing and even in policymaking to include training on green computing in the curriculum. Other recommendations from the study included the inclusion of budgets for green computing and the development of green ICT personnel.

In the past, there has been an increase in the adoption and use of cloud computing orchestrated by its efficiency, availability, and scalability. This increased adoption has led to an increased workload in the cloud. This ideally means increased energy consumption in the cloud by the data centres housing all the services the cloud provides leaving behind carbon footprints. Techniques like virtualization, task scheduling, hardware-oriented optimization, use of renewable energy sources, power management techniques, and use of green service level agreements were some of the options found to help reduce carbon emissions from data centres (Aslam & Kaur, 2018).

2018 research conducted by Barasa et. al. in Kenya on trends in green computing clearly outlined that many pieces of research that were being carried out in this field revolved around cost-saving with less emphasis on environmental sustainability (Barasa, Kimia, Motochi, & Barasa, 2018). Many consumers of IT products were more concerned with the performance and efficiency of such systems without considering their impact on the environment.

Developing countries have encountered varied challenges in the adoption of green computing practices in their organizations. Research done by Donatien et al. noted that in Burundi, the uptake and use of technology in institutions of higher learning are relatively low. The research surveyed private and public universities. Among the key concerns were ICT governance, power consumption, personnel capacity, and green computing status to be key concerns towards adopting green computing by these institutions (Donatien, Barasa, & Franklin, 2021). A

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framework was developed based on the findings to help these institutions adopt green computing.

Gu et al conducted research on low-carbon edge computing and proposed the use of the new deep reinforcement technique (DRL) to address the challenges of high inefficient energy consumption in computing, especially in service management and energy scheduling. The proposed algorithm proved to perform better than the traditional methods as it proposes scheduling of computing resources based on user demands (Gu, Zhang, Wang, Zeng, & Jin, 2023). Using real-world examples, the research confirmed that the proposed approach is more efficient than the traditional model-based solutions.

METHODOLOGY

A systematic review of previous studies is a research method that involves searching, locating, and evaluating readily available data on the internet (Brereton, Kitchenham, Budgen, Turner, & Khalil, 2007). Such kind of research is also referred to as desktop research. This form of research is very important as it makes use of free resources such as the internet that is freely available. Reliable sources were used in this study. At the first stage, the search criteria are determined, inclusion and exclusion criteria are also determined, selection of studies that meet the criteria and design of the research questions.

A criterion for inclusion and exclusion was also determined as listed below.

Inclusion

- Only studies related to green computing were selected.
- Only studies written in the English language were considered.
- The study must include at least experimental or analytical aspects of green computing.
- Only studies with open access were considered.

Exclusion

- Research studies were done before 2022 and after 2023.
- Studies that review other green computing and related research work.
- Any duplicated research articles.

With systematic review, the research needs to use a standardized approach in selecting and reviewing previous research works. In this research, the focus was on studies done and published in IEEE, which is one of the most preferred peer-reviewed journals for scientific articles. In this step, necessary mechanisms were put in place to ensure that inclusion and exclusion criteria are well applied and that only intended studies are included. Several keywords were used to locate the studies. They include green computing, green ICT, smart grid, cloud computing, green AI, green IoT, green data mining, green procurement, green databases, and environmentally friendly computing.

Within the journal website, the necessary search criteria (year published, research area) were applied and a total of 330 articles were found to be relevant. These results were extracted and tabulated based on the research title to help exclude all studies that reviewed other works as well as exclude any research that may not have comprehensively covered green computing. Applying this criterion, a further 13 studies were dropped leaving the research with 317 studies to analyse. On further reviewing their abstracts, a further 243 research studies were found not to be aligning with green computing hence they were dropped from the analysis. These studies had aspects of computing e.g., cloud computing, edge computing, and intelligent green systems but their research theme was not in green computing.

Upon successful selection of the relevant research studies, research topics were used to classify this research into different research groups in green computing. A total of 75 research studies were found to be relevant and hence proceeded to the analysis stage.

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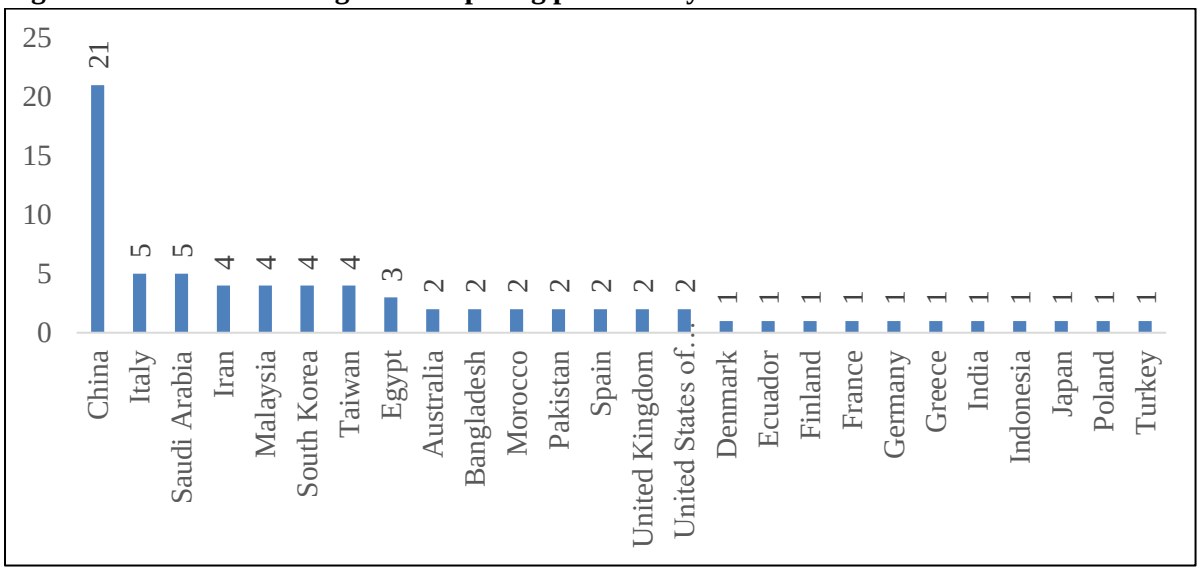
STUDY FINDING AND RESULT ANALYSIS

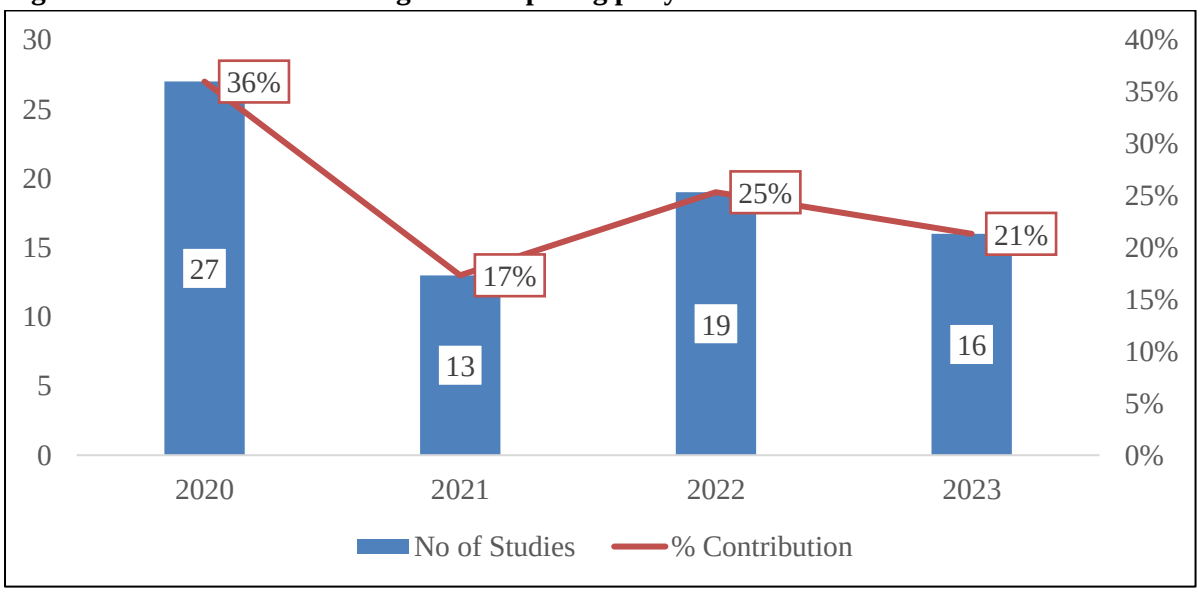
Analysis was carried out on the 75 studies that were found to be relevant to this research and results were organized into several categories including the country of origin, specific research areas in green computing, and year research was carried out among others. China topped as the country with the highest number of research studies in green computing. Twenty-one (21) studies were carried out in China (28%) followed by Italy and Saudi Arabia with each having 5 studies (7%) as shown in the figure 2 below.

Figure 2: No. of studies in green computing per country



For the years under interest i.e., 2020 to 2023, majority of the research in green computing was done in 2020(36%) followed by 2022 (25%), 2023 (21%) and 2021 at 17% as shown in the table below.

Figure 3: Number of studies in green computing per year from 2020 to 2023



Analysis for the different areas of research was done and Green IoT (26%), Edge computing (16%), cloud computing (12%) and green networks/communication (11%) had the greatest number of studies done as shown in the table below.

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Table 1: Number of studies in green computing per research area

Research Area	No of Studies	% Studies
Green IoT	20	27%
Edge Computing	12	16%
Cloud Computing	9	12%
Green Network/Communication	8	11%
Green Artificial Intelligence	7	9%
Green Datacenters	6	8%
Green Algorithms	4	5%
Green Software Development	3	4%
Green Blockchain	2	3%
Green Manufacturing	2	3%
Micro Grids	1	1%
Green IT Management	1	1%

Areas of Green Computing

Green computing covers a wide area of all computing activities whose main aim is environmental sustainability. As per the years and journals sampled, the 75 studies' areas were broadly classified into 12 areas, as in Figure 4 above. It is important to note that some studies focused on more than one of these areas. However, the study had to find and classify those journals into one category.

Green Internet of Things (IoT)

The Internet of Things (IoT) has greatly and positively contributed to economic growth by connecting and allowing devices to communicate. However, with the increased number of devices, there is increased energy consumption and increased e-waste, both of which affect the environment negatively. Therefore, it is important for energy efficient IoT devices to be developed (Alsharif, Jahid, Kelechi, & Kannadasan, 2023). Future recommendations from the review include a social interaction-assisted resource-sharing paradigm for device-to-device communication that can improve the utilization of resources in green IoT (López et al., 2023).

Future trends in green IoT includes energy efficient machine to machine communication, the development of environment-friendly and energy-efficient wireless sensor networks, energy-efficient radio frequency identification and energy-efficient microcontroller unit and integrated circuits (Alsharif, Jahid, Kelechi, & Kannadasan, 2023).

Green Edge Computing

Edge computing aims to take the computing and processing of data closer to the source. This technology has the potential to reduce energy consumption as there is no need for more powerful servers, low latency, and quick responses as requests are processed and responded to in near real-time (Khanna, Pareek, Goyal, & Chaurasia, 2023). Serving requests nearer to where they were generated ensures that there is increased performance, and lesser energy consumption as requests do not need to move through several nodes to be allocated a server to process the request (Binucci, Banelli, Lorenzo, & Barbarossa, 2023). Apart from saving energy consumption, it also improves processing time and reduces network traffic among other things.

Green Cloud Computing and Green Data Centres

Green cloud computing aims to reduce the negative effects cloud computing has on the environment. Cloud computing and data centres go hand in hand as the data centres play a central role in cloud computing. This has led to increased research activities in this area of green computing. This has called for the development of energy-efficient hybrid systems, low carbon-emitting clouds, VM migration optimized algorithms, load-balancing, recyclability and re-usability, optimization of data centres and server

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virtualization has played a key role in reducing energy consumption in the cloud. Development and deployment of energy-efficient algorithms (Zhou et al., 2020). Green data centres will continue to increase in popularity, making the development of more efficient and cost-effective cooling systems important, utilization of greener energy sources to power the servers, and the development of green servers.

Green Networks/Communication

With the 6G Network, it is anticipated that network systems will perform faster and improve request-response time compared to 5G (Ranju, 2022). 6G has the potential to improve green communication as network latency and performance will generally improve. Since this technology is currently under development. It is important for green computing aspects to be built into it to ensure that it is energy efficient, unlike its predecessors that were developed without considering this (Bolla, Bruschi, Lombardo, & Siccardi, 2023).

Green Artificial Intelligence Algorithm

Green artificial intelligence covers all research aspects of the application and use of energy-efficient AI techniques that promote less emission of carbon footprints and efficient use of energy. In the recent past, there has been a tremendous increase in the incorporation of machine learning in nearly all aspects of human life. This ideally means machine learning algorithms and models must be designed in a more environmentally friendly way. Machine learning involves the use of large datasets to learn hidden patterns in data to make decisions. The model will use a lot of energy to run such a data set and given that data keeps on trickling in from time to time, then the model keeps on re-learning now and again. This worsens the situation. It is therefore important for green AI algorithms to be developed that can effectively manage computing resources while minimizing negative environmental effects (Tai, Lin, & Hsiao, 2023).

Other Green Computing Areas

Other research areas in green computing include research in green software development, green blockchain, green manufacturing, green IT management and microgrids. All these areas are very important and crucial in the improvements in green computing. Other areas that might have not been featured in this analysis that cover green computing include green procurement, green e-commerce, green e-gov, green databases and green data mining.

Future of Green Computing

From the analysis above, there is a lot of research being done in green computing. Each day, there is an increased need for the development of more environmentally friendly computing systems. Right from developing green hardware devices i.e., servers, computers, mobile devices, sensors, networking devices and others to developing green software development frameworks, algorithms, and models. Since there will be an increased number of devices over time, the most reliable remedy available to deal with this problem is as discussed above.

Each of the areas covered above has a greater potential to positively impact human life, hence their increased adoption. For example, IoT has the potential of interconnecting all devices and allowing seamless communication. Future research in this area will include the development of IoT devices that consume less power as well as devices with long life to ensure we do not have increased e-waste. Also, the development of optimized green IoT software solutions will play a key role in reducing the negative effect.

Other options like increased generation of green energy using solar or wind-powered options will also see increased research. Renewable energy sources will play a central role in minimizing energy waste. The green policy will also help reduce energy waste by promoting the culture of purchasing green items. This will help reduce carbon footprints, among other things. It will also be important to make the public aware of the importance of conserving the environment by

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promoting green education. Incorporation of this into the curriculum is key in ensuring everyone is aware of how their activities contribute towards the environment.

Limitation

This study only considered articles published in the IEEE with open access for analysis. This is a limitation as articles published in other journals were not considered hence it could miss very essential and insightful information. It is also possible that during analysis and classification, some articles might have been misclassified.

CONCLUSION

Green computing is an important approach towards addressing the negative impact technology has on the environment. It encompasses all activities and practices such as e-waste management, energy efficiency software development practices, optimized hardware components and use of environmentally friendly energy sources. Through implementing green computing, organizations can reduce carbon footprints, minimize their negative impact on the environment and help conserve natural resources. Organisations are migrating their services to the cloud which has led to increased use of energy by cloud computing devices hence high research interests in cloud computing including the design and development of green data centres.

In conclusion, there is increased interest in researching in the domain of green IoT, edge and cloud computing. This means that organizations should focus and redirect a lot of resources towards developing energy-efficient hardware and software systems that support IoT devices. This is due to the increase and adoption of IoT technologies.

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