Green Computing for Energy Transition: A Survey

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***Abstract*—The global information technology (IT) industry accounts for approximately 2% of the world's greenhouse gas emissions, equivalent to the aviation industry's emissions. Moreover, IT energy consumption is projected to increase by 5% annually, and the industry is expected to consume 21% of the world's electricity by 2030. Therefore, there is a growing urgency to develop and implement sustainable computing practices that reduce energy consumption and mitigate the environmental impact of the computing industry. Green computing has emerged as a vital area of research due to the increasing demand for environmentally sustainable practices in the computing industry. To contribute to this dialogue, this paper presents a comprehensive survey of 74 articles related to green computing and its various subtopics. These subtopics include sustainable practices, energy-efficient hardware design, software optimization, and the use of renewable energy sources. Additionally, the survey analyses the role of green algorithms in reducing energy consumption and carbon footprint in computing systems. Our findings highlight the significance of adopting green computing practices to mitigate the adverse impact of computing on the environment, including greenhouse gas emissions, energy consumption, and waste generation. Our survey underscores the growing interest in green computing, as evidenced by the increasing number of articles and research studies dedicated to this topic. Furthermore, our analysis of the existing literature highlights the need for further research in this area to develop more effective and sustainable solutions. Overall, the survey serves as a valuable resource for researchers, practitioners, and policymakers to understand the current state of research in green computing and to identify areas for future research. By promoting sustainable practices in the computing industry, we can contribute to a more environmentally sustainable future for our planet.**

***Index Terms*—Green Algorithms, Sustainable, Green Computing, Carbon Footprint, Energy Transition.**

I. Introduction

The quest for sustainable, renewable and clean energy has been constant in recent years [1]–[3]. The current concern about energy generation is global and has prompted several researchers to study and develop devices capable of harnessing renewable and sustainable sources. The reason for it is that issues such as climate change, energy crisis, and environmental pollution are progressively worsening and demanding immediate attention, and it leads countries to stipulate low-carbon policies [4]–[10]. The term "green computing" encompasses a wide range of practices, technologies, and methodologies that can help reduce the environmental impact of computing systems [11]–[13]. These include designing more energy-efficient hardware [14], optimizing software to reduce energy consumption [15]–[17], using renewable energy sources to power computing systems [18]–[20], and implementing more sustainable practices in data centres and other computing facilities [21] [22].

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As the worldwide demand for computing technologies keeps expanding, the necessity for green computing has grown progressively vital in recent years. Estimates suggest that the energy consumption of some data centres will change the characteristics of energy consumption in some nations. For example, Zhu et. al. [23] present the characteristics and tendency of energy consumption in data centres. The information technology (IT) industry is a significant contributor to global greenhouse gas emissions, accounting for approximately 2% of the world's total emissions, which is equivalent to the aviation industry's emissions. This figure is projected to increase in the coming years, as IT energy consumption is expected to rise by 5% annually. By 2030, the IT industry is forecasted to consume 21% of the world's electricity, making it a significant consumer of energy resources [24], [25]. This trend is anticipated to persist in the upcoming years, emphasizing the significance of developing more sustainable computing technologies and practices. In response to these challenges, a variety of solutions are being explored by researchers, engineers, and policymakers. These solutions include the development of novel hardware architectures [26] [27] and the implementation of more efficient cooling systems in data centres [28] [29]. That means a new approach in with designing, developing, and using computer systems is used in an environmentally sustainable way. It involves reducing the energy consumption, waste, and carbon footprint of computing systems.

The adoption of green computing is primarily driven by the need to reduce the impact of computing systems on the environment. The usage of fossil fuels to generate electricity for computing systems results in a significant amount of greenhouse gas emissions. Therefore, by reducing the energy consumption of these systems, we can effectively minimize our carbon footprint and contribute towards mitigating the effects of climate change. The design of more sustainable and efficient computing technologies is crucial for achieving this goal, and collaborative efforts in this regard can aid in diminishing the environmental impact of computing. Such initiatives can pave the way for a more sustainable future for our planet.

To underscore the importance of this theme, this paper provides an extensive survey of the literature on green computing, including an in-depth analysis of the primary solutions that have been adopted in recent years. This survey highlights the growing interest in green computing, as evidenced by the increasing number of articles and research studies dedicated to this topic. One promising area of development is the use of green algorithms, which are designed to reduce the energy consumption of computing systems while maintaining performance levels. By adopting such solutions, it is possible to significantly reduce the environmental impact of computing systems, thereby promoting sustainability in the industry. To sum up, this paper aims to contribute to the ongoing dialogue on green computing, while also serving as a valuable resource for researchers, policymakers, and other stakeholders seeking to promote sustainability in the computing industry.

The rest of this paper is laid out as follows: Section II establishes the necessary background material to understand the main idea of the work. Then, the proposed method is explained in Section III. The results and the mainly works in green computing and green algorithms are presented in Section IV. Section V discusses the results and, finally, Section VI concludes the study.

II. Background

A. Green Computing

Green computing is a concept that has emerged in recent years as a response to the growing concern over the environmental impact of the computing industry. With the rise of digital technologies and the increasing use of computing devices in our daily lives, it has become increasingly important to consider the environmental impact of these systems [30]. Green computing refers to the design, development, and implementation of computing systems that are environmentally sustainable. The main goal is to minimize the negative impact of computing on the environment, including reducing energy consumption, minimizing greenhouse gas emissions, and decreasing waste generation. This is achieved by adopting a range of sustainable practices, including the use of energy-efficient hardware and software, the implementation of efficient cooling systems, the use of renewable energy sources, and the adoption of sustainable data centre practices [31], [32].

The adoption of green computing practices has become increasingly important in recent years, as the computing industry continues to grow and consume more energy and resources. According to a report by the International Energy Agency, data centres and networks account for 1% [33] of global electricity consumption, a figure that is expected to triple by 2030 if no action is taken to improve energy efficiency in the sector. The report also notes that energy efficiency measures could save up to 50% of the electricity consumed by data centres and networks. To address this growing concern, researchers, and practitioners in the field of green computing have been working to develop more sustainable computing practices. One area of research has focused on the development of energy-efficient hardware and software. For example, researchers have developed more energy-efficient processors and memory systems that can significantly reduce energy consumption in computing systems. They have also developed software algorithms that optimize system performance while minimizing energy consumption.

Another area of research in green computing is the use of renewable energy sources to power computing systems. This includes the use of solar, wind, and hydropower to generate electricity for data centres and other computing facilities. According to a report by the Natural Resources Defence Council, using renewable energy sources to power data centres could reduce carbon emissions by up to 90%. Green computing also emphasizes the need for sustainable computing practices beyond the initial development and implementation of systems. This includes the proper disposal and recycling of electronic waste and the adoption of sustainable practices in the entire life cycle of computing systems. For example, researchers have developed new recycling methods that can extract valuable materials from electronic waste and reduce the amount of waste that ends up in landfills.

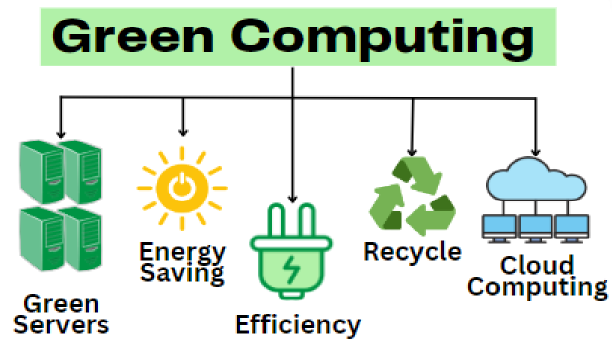

Fig. 1. Different applications of Green Computing: Illustrating the diverse areas where it can make a positive impact on the Environment and Society.

B. Green Algorithm

One area of research in green computing has focused on the development of energy-efficient algorithms. Green algorithms are software programs that have been designed to optimize system performance while minimizing energy consumption. They are a key component of green computing, as they help reduce the energy consumption of computing systems, which in turn reduces the negative impact of computing on the environment. Researchers have developed various algorithms that can significantly reduce energy consumption in computing systems. For instance, the dynamic voltage scaling (DVS) algorithm is a popular approach used in mobile devices to reduce energy consumption [34]. The algorithm dynamically adjusts the voltage and frequency of the processor to match the computing workload, thereby reducing energy consumption while maintaining performance.

Another example of a green algorithm is the sleep scheduling algorithm. This algorithm is used in wireless sensor networks to minimize energy consumption by scheduling sleep periods for the sensors when they are not needed. In other way, approaches to developing green algorithms include energy-aware task scheduling, cache management, and workload distribution. Researchers have developed various algorithms in these areas to minimize energy consumption in computing systems.

In conclusion, green algorithms are an important area of research in green computing, and they have the potential to significantly reduce the energy consumption of computing systems. These algorithms can be used in various applications, such as mobile devices, wireless sensor networks, and cloud computing environments. By optimizing system performance while minimizing energy consumption, green algorithms help reduce the negative impact of computing on the environment.

III. Methodology

In this study, a comprehensive literature review was conducted between 2012 and the present day to examine the potential benefits of using green computing. The primary objective of the literature review was to identify existing research on the topic and synthesize the findings to provide a comprehensive overview of the current state of research in this field. The process for conducting the literature review was established after careful consideration of the research questions and objectives. As shown in Figure 2, the steps involved in the review process included identifying relevant databases, selecting appropriate search terms, screening and selecting relevant articles, and synthesizing the findings. These steps were carefully followed to ensure that the review process was rigorous and comprehensive, and that the resulting findings were valid and reliable. The authors searched four main sources, namely SCOPUS, WEB OF SCIENCE, IEEE XPLORE and PUBLISH OR PERISH using specific search queries that were tailored to each source. The queries were formulated as it follows: *(TITLE ("green computing") OR TITLE ("green algorithm") OR TITLE "green code")) AND (TITLE-ABS-KEY "carbon footprint") OR TITLE-ABS-KEY "energy transition") OR TITLE-ABS-KEY ("energy efficiency")) AND PUBYEAR > 2012 AND PUBYEAR < 2024*. A total of 103 articles were found in Scopus, 37 in Web of Science, 31 in IEEE Xplore and 37 in Publish or Perish.

Following this initial screening, the authors conducted a thorough evaluation of the abstracts of the selected papers to assess their relevance and suitability for inclusion in the review. Duplicate articles were excluded, and some papers were included based on the authors' expertise in the field. Through a rigorous and detailed screening process, a total of 74 articles were identified as suitable for inclusion in the review, as depicted in Figure 3. To gain a comprehensive understanding of the applications and to comprehend the state-of-the-art, a full-text examination was conducted on the selected articles.

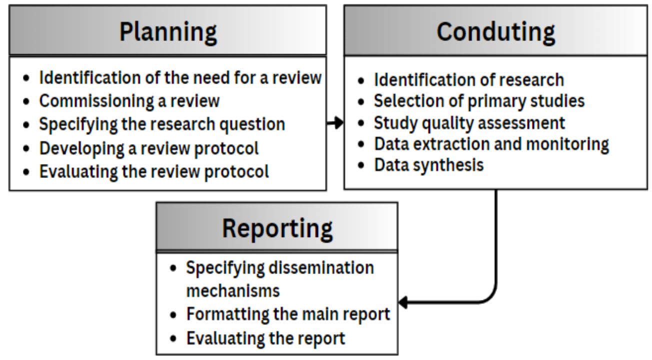

Fig. 2. Three Stages of the Proposed Methodology for the Bibliographic Review. The first stage is the selection of the databases used for the search, followed by the second stage of the application of the inclusion and exclusion criteria to the articles found. The third and final stage is the analysis of the selected articles and the extraction of relevant information, such as the areas and keywords addressed in the articles.

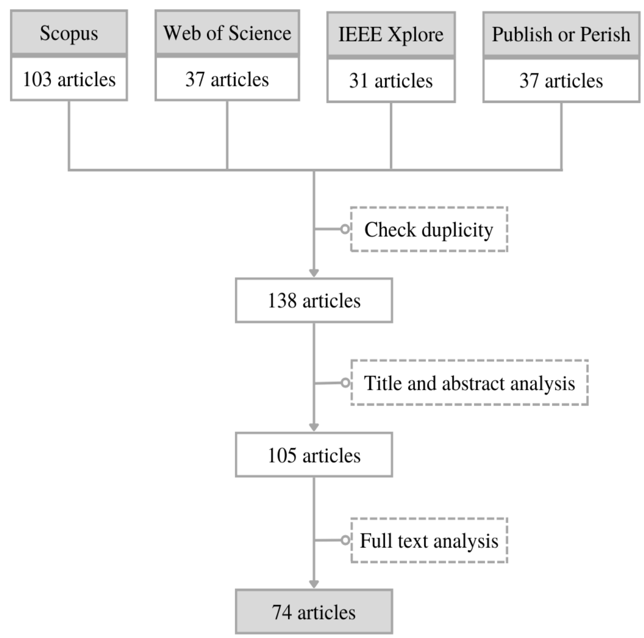

Fig. 3. Stages of conducting the bibliographic review: (1) Search base, filtering the articles by year of publication and language; (2) Filter 1: removal of duplicate articles; (3) Filter 2: application of inclusion and exclusion criteria in the title and summary; and (4) Filter 3: application of inclusion criteria and deletion in full text.

IV. Results

The article, "*Ten simple rules to make your computing more environmentally sustainable*" [35], presents a practical and accessible set of guidelines for reducing the environmental impact of computational activities. The study highlights the significant carbon footprint associated with technology and computational activities, and the importance of taking action to mitigate this impact. The authors provide ten rules for more sustainable computing practices, including choosing energy-efficient hardware, using virtual meetings, reducing energy consumption, and sharing resources. The guidelines are straightforward and can be implemented by researchers and practitioners in various fields, from bioinformatics to data science and beyond. The 10 rules are:

1) Calculate the carbon footprint of your work.
2) Include the carbon footprint in your cost–benefit analysis.
3) Keep, repair, and reuse devices to minimise electronic waste.
4) Choose your computing facility
5) Choose your hardware carefully
6) Increase efficiency of the code
7) Be a frugal analyst
8) Releasing a new software? Make its hardware requirements and carbon footprint clear
9) Be aware of unanticipated consequences of improved software efficiency
10) Offset your carbon footprint

One of the significant contributions of this study is its potential to promote more sustainable computing practices across various fields. The authors point the importance of individual and collective action to reduce the carbon footprint of computational activities, and the guidelines they provide are a practical starting point for achieving this. Furthermore, the study highlights the importance of considering the environmental impact of technology and computational activities, an issue that is becoming increasingly urgent as the world faces the challenges of climate change. By promoting more sustainable computing practices, this study offers a concrete way for individuals and organizations to contribute to a more sustainable future.

In "*Green Computing and Carbon Footprint Management in the IT Sectors*" [36], the author discusses the importance of green computing and its potential to reduce the carbon footprint of the IT industry. The article highlights the energy consumption and associated carbon emissions of the IT sector and provides an overview of various approaches and technologies that can promote more sustainable computing practices, including energy-efficient hardware and cloud computing. The author also stresses the role of policy and regulation in promoting sustainable computing practices and provides examples of successful initiatives. This informative article offers a comprehensive understanding of green computing and its potential to contribute to a more sustainable future.

In "*The Carbon Footprint of Bioinformatic*" [37], the authors aim to estimate the carbon footprint associated with bioinformatics research, an important field in molecular biology. The study found that data storage and computing hardware are responsible for the majority of emissions, and that optimizing software code, using energy-efficient hardware, and employing cloud computing can reduce the carbon footprint of bioinformatics research. The results of this study provide valuable insights into the environmental impact of bioinformatics research and offer practical strategies for reducing its carbon footprint. By using sustainable computing practices, bioinformatics researchers can contribute to a more sustainable future for the IT sector and beyond.

A. Green Computing

The article "*Green computing: Awareness and practices*" [38] highlights the need for more sustainable computing practices, and the role of awareness in promoting them. Although awareness of green computing is generally high, the study found that many respondents were not practising environmentally sustainable computing. Therefore, the authors suggest more efforts are needed to raise awareness and promote the adoption of sustainable computing practices. Similarly, the in [39] the author emphasizes the need for sustainable computing practices and presents a review of the latest green computing technologies. The article also discusses the role of sustainable design in green computing, such as the use of eco-friendly materials and the design of energy-efficient buildings. In addition, the articles [40] and [34] both discuss the potential for mobile computing to contribute to more sustainable computing practices. They emphasize the importance of considering energy consumption and sustainability in the design and use of mobile computing technologies. Moreover, the article "*Meeting green computing challenges*" [41] proposes solutions for reducing the environmental impact of computing, such as virtualization, power management, and renewable energy use. The article also highlights the importance of designing eco-friendly electronic products and minimizing waste during manufacturing.

It is important to highlight these four articles below about various aspects of green computing, including its unusual nature, strategies for reducing energy consumption, potential benefits for the environment and society, and the importance of collaboration between different stakeholders in promoting its adoption.

- "*Energy oddities, part 2: Why green computing is odd*" [42] highlights the unusual nature of green computing. It discusses how the goal of green computing is to reduce energy consumption and environmental impact, which is a deviation from the traditional objective of computing – to maximize performance and processing power. The article presents the paradox of green computing, which is that by trying to reduce energy consumption, we end up consuming more energy in the process. This is because the process of making computing green involves the use of additional hardware and software, which ultimately results in more energy consumption. Cameron argues that we need to find a balance between the goals of green computing and the traditional objectives of computing.
- "*Power-saving policies for annual energy cost savings in green computing*" [43] propose power-saving policies for reducing the energy consumption of computing systems. The article presents a model that calculates the energy consumption and cost of a computing system based on its power usage. The proposed policies aim to reduce energy consumption and cost while maintaining the performance of the computing system. The policies include strategies such as dynamic voltage and frequency scaling, power-aware task scheduling, and power-aware virtual machine placement. The authors show that implementing these policies can result in significant energy and cost savings.
- "*Green computing a way towards environmentally sustainable future*" [44] presents an overview of green computing and its potential to contribute towards a sustainable future. The article discusses the various challenges facing the IT industry in terms of energy consumption and environmental impact. The author presents green computing as a solution to these challenges and discusses the various strategies and technologies used to make computing more environmentally friendly. The article also highlights the benefits of green computing, including reduced energy consumption, lower costs, and a positive impact on the environment.
- "*Green Computing: A Contribution Towards Better Future*" [45] discuss the importance of green computing in creating a better future for humanity. The authors present green computing as a key strategy for reducing energy consumption and carbon emissions, which is critical in the face of the current climate crisis. The article discusses various technologies and strategies used in green computing, including virtualization, cloud computing, and energy-efficient hardware. The authors emphasize the need for collaboration between different stakeholders, including industry, government, and academia, to promote the adoption of green computing practices and technologies. The article concludes by highlighting the

importance of green computing in creating a sustainable and equitable future.

The education sector is also recognizing the importance of green computing, with several studies proposing various models and frameworks for its adoption. Agrawal et al. (2014) [46] examine the use of virtual desktop infrastructure in universities, while Hanief et al. (2019) [47] propose a model for the adoption of green computing in Indonesian higher education. Podder et al. (2022) [48] propose a research initiative on sustainable education systems, and Mohabuth (2022) [49] presents a comprehensive framework for the implementation of green computing in universities.

As the negative impact of traditional computing on the environment has become more apparent. As a result, researchers have proposed various approaches to reduce the energy consumption of cloud data centres, which are known to be one of the most significant contributors to the carbon footprint of the IT industry. Arthi and Shahul Hamead [50] proposed an energy-aware cloud service provisioning approach to improve energy efficiency in cloud data centres. They used a genetic algorithm to optimize the allocation of resources and minimize energy consumption. Similarly, Bhattacherjee et al. [51] proposed energy-efficient migration techniques for cloud environments, such as virtual machine migration and consolidation, to reduce energy consumption. Hu et al. [52] conducted a survey on green computing in cloud environments and identified various approaches to achieve energy efficiency, such as dynamic resource allocation and virtualization. Jayalath et al. [53] reviewed the adoption of green computing attributes and vendor-specific implementations in cloud computing. They identified various techniques for achieving green computing, such as energy-efficient hardware and software design, and renewable energy sources. Liu et al. [54] proposed energy-aware task scheduling strategies with quality of service constraints for green computing in cloud data centres. They used a genetic algorithm to optimize task scheduling and minimize energy consumption while ensuring quality of service. Usman et al. [55] proposed an energy-efficient virtual machine allocation technique using the flower pollination algorithm in cloud data centres. They used this technique to minimize energy consumption while maintaining service level agreements. Verma et al. [56] proposed a network virtualization approach to enable green computing in cloud environments. They used network virtualization to reduce energy consumption and improve resource utilization. Finally, Yang [57] proposed an energy-efficient cloud data centre with a fair service level agreement for green computing. They used a fairness index to ensure that each user received a fair share of resources while minimizing energy consumption. These studies demonstrate the importance of energy-efficient approaches in cloud computing and provide various techniques to achieve green computing.

Green computing is also a crucial area of research to minimize the energy consumption of computing devices in the context of the Internet of Things (IoT) and Industrial Internet of Things (IIoT) systems. To achieve this objective, researchers have proposed different techniques and algorithms for energy-efficient server consolidation and virtual machine allocation in cloud data centres, such as the resource-utilization-aware algorithm proposed by Han et al. [58] and the energy-oriented path and message scheduling approach proposed by Farhan et al. [59]. Jaiswal et al. [60] proposed a time-slotted simultaneous wireless information and power transfer scheme for green computing in IoT. To secure the IoT environment, Rani et al. [61] presented a lightweight postquantum signature for the Internet of Everything (IoE). Additionally, Jaiswal et al. [62] proposed an optimization technique using SARSA-based reinforcement learning for energy allocation in heterogeneous IoT systems. To reduce energy consumption in IoT communications, Kallam et al. [63] presented a low-energy communication process using a green computing approach. Finally, Germain-Renaud et al. [64] describes the Green Computing Observatory, which is a data curation approach for Green IT that gathers and analyses data related to the energy consumption of IT equipment to enable informed decision-making for energy efficiency improvements.

In the context of wireless sensor networks, Khasawneh et al. [65] proposed a pressure-centric energy modelling approach to improve the energy efficiency of underwater wireless sensor networks (UWSNs) using green computing techniques. In another study, Fernandas and Vasanthi [66] proposed an energy-efficient mechanism for green computing in wireless storage area networks (SANs). They suggested using techniques such as power management, disk spindown, and virtualization to reduce energy consumption. Richariya and Motwani [67] applied green computing to wireless sensor networks (WSNs) and proposed an energy-efficient computing approach using techniques such as dynamic voltage scaling and duty cycling. Shrivastava et al. [68] implemented a green computing control unit on Zynq FPGA for green communication in wireless networks. They suggested using the dynamic voltage and frequency scaling technique to reduce energy consumption. Overall, these studies suggest that the application of green computing techniques can significantly reduce energy consumption and improve the energy efficiency of wireless networks.

The articles [69]–[72] are reports and surveys related to the topic of green computing. Stolf and Monteil provide a report on Collaborative and Autonomic Green Computing [69], while their previous work presents a summary report on the same topic [70]. Brunvand et al. [73] conducted a case study on the harmful effects of dark silicon on green computing. Tiwari et al. provide a review on green computing implementation using efficient techniques [71]. Finally, Liao and Chen conducted a bibliometric analysis and mapping of the landscape of green communications and green computing [72]. These reports and surveys contribute to the literature on green computing, providing insights on various aspects of the field.

This paragraph cites 20 articles on various aspects of green computing, including energy-efficient architecture design, tools for green computing, and success factors for implementing green computing initiatives. Hatwar and Shrawankar (2014) [74] proposed a VM management approach, while Tariq et al. (2019) [75] presented a meta-heuristic for green computing. Nagy et al. (2019) [76] introduced tools that support green computing in Erlang, and Al-Zamil and Saudagar (2020) [77] discussed the challenges and drivers of applying green computing in sustainable agriculture. Krithika and Keerthana (2013) [78] compared Intel and AMD processors in terms of green computing, while Khare and Jain (2013) [79] discussed the prospects of near-threshold voltage design for green computing. Nayak and Bhat (2022) [80] presented low-power architecture strategies, and Sukarman and Putri (2018) [81] proposed a green IT policy in Indonesia. Mogale et al. (2018) [82] introduced a hybrid multicore architecture for green computing, and Joshi et al. (2012) [83] presented a multi-layer approach to designing energy-efficient digital circuits and manycore architectures. Lee et al. (2011) [84] presented a profile-based building energy-saving service, and Guo et al. (2016) [85] discussed multi-label classification methods for green computing. Khan et al. (2019) [86] presented a success factors model for green computing implementations, while Kumar (2022) [87] discussed embracing green computing in molecular phylogenetics. Asnani et al. (2019) [88] proposed producing green computing images to optimize power consumption in OLED-based displays, and Rodrigues et al. (2018) [89] presented a navigation phases platform for green computing for UAVs. Kshirsagar et al. (2021) [90] presented GREECOPE, a green computing approach with the piezoelectric effect, and Niyato et al. (2009) [91] proposes an optimal power management strategy for server farms that considers workload distribution and energy efficiency to support green computing. Finally, Cai et al. (2019) [92] presented an energy-efficiency-aware resource allocation strategy for multi-granularity provision for green computing, and Raja (2022) [93] presents a future perspective on green computing and provides an operational analysis of a data centre.

The number of articles on green computing indicates that the field is of growing interest to researchers and professionals who are looking to reduce the environmental impact of computing. These articles cover a wide range of topics, including hardware design, resource allocation, and policy implementation. It is evident that there is a need for more environmentally friendly computing practices, and these articles provide valuable insights into how this can be achieved. As technology continues to advance, it will be important for researchers and professionals to consider the environmental impact of their work and strive towards more sustainable computing practices.

B. Green Algorithms

A way to reduce energy consumption is through software optimization. A good technique to achieve that is the green algorithms. Green algorithms are designed to optimize energy consumption by reducing the number of operations required to perform a particular task. For example, a green algorithm might prioritize tasks that require less energy or reduce the number of computations required to complete a task.

The article, "*Green Algorithms: Quantifying the Carbon Footprint of Computation*" [30], highlights the importance of measuring the carbon footprint of computational activities. The authors argue that the increasing use of technology and the associated rise in energy consumption can have a significant impact on the environment, and it is crucial to quantify the carbon footprint of these activities. The study proposes a method for estimating the carbon footprint of algorithms and presents several case studies demonstrating the effectiveness of the approach. The importance of this study lies in its potential to inform decisions regarding the development of energy-efficient algorithms and the optimization of computational activities to reduce their carbon footprint. This is especially relevant given the growing concern over the impact of technology on the environment and the need for sustainable development. Figure 4 presents the graphical interface of the green algorithm website in operation and the variety of analyses carried out.

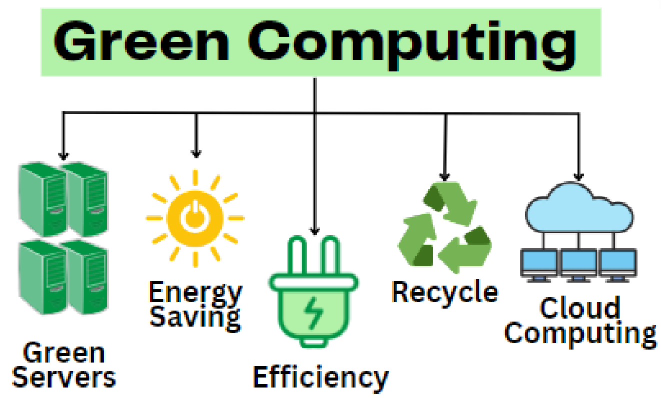

Fig. 4. Graphical interface of the green algorithm website. Source: [30].

Regarding green algorithms, there are some papers applied to cloud computing: "*Green algorithm to reduce the energy consumption in cloud computing data centres*" [94] and "P*ower management in cloud computing using green algorithm*" [95] both propose the use of a green algorithm to improve energy efficiency in cloud computing data centres. The articles suggest that by efficiently allocating virtual machines to physical servers, energy consumption can be significantly reduced, leading to cost savings and environmental benefits. However, while the focus of [94] is on reducing energy consumption, [95] emphasizes the importance of power management in cloud computing, including the need to minimize power wastage and ensure efficient resource utilization. Another good example of green algorithm applied to cloud computing is given by Theja and Khadar Babu [96] where the authors propose a new approach to virtual machine (VM) consolidation in large-scale cloud infrastructures. The authors suggest using an adaptive genetic algorithm to optimize VM placement, taking into account both quality of service (QoS) requirements and energy efficiency. The article presents a detailed analysis of the proposed scheme, including experimental results demonstrating its effectiveness in reducing energy consumption while maintaining QoS. The authors argue that their approach is more robust than existing VM consolidation schemes and can be applied to large-scale cloud infrastructures to achieve significant energy savings. Overall, the three articles provide a valuable contribution to the field of green computing and cloud infrastructure optimization, highlighting the importance of considering both QoS and energy efficiency in VM consolidation and also offering practical solutions when adopting green technologies in the data centre industry.

Shelar et al. [97] and Prakash et al. [98] use green algorithms to reduce energy consumption in wireless networks. Shelar et al. suggest that by clustering underwater wireless sensor networks (UWSNs) based on the optical signal-to-noise ratio (OSNR) of the optical signals, energy consumption can be reduced while maintaining network performance. The algorithm proposed by the authors achieves a 30% reduction in energy consumption and a 25% increase in network lifetime compared to existing algorithms. In the other hand, Prakash et al. suggest that by optimising the network topology and power levels of the nodes, energy consumption can be significantly reduced while maintaining network performance. They present experimental results that show a 20% reduction in energy consumption and also show that the proposed algorithm can handle network topology changes and dynamically adapt to changes in traffic load, making it suitable for real-world wireless mesh networks (WMN) applications.

A common task encountered in scientific computing, engineering, and data analysis is to solve sparse linear systems. In [99] the authors discuss the use of graphics processing units (GPUs) to solve sparse linear systems. They propose a parallel algorithm that can efficiently solve such systems using GPUs, thereby providing faster and more environmentally-friendly computations. Some results of this paper include: the demonstration of a parallel algorithm, based on the conjugate gradient method, that can be used to solve sparse linear systems using GPUs; a demonstration that use of GPUs can significantly improve the performance of the conjugate gradient method; a discussion about environmental benefits of using GPUs for scientific computing and a number of numerical experiments that demonstrate the effectiveness of the proposed algorithm. Further, the authors demonstrate that the parallel algorithm proposed in the article is shown to be faster than traditional CPU-based algorithms by a factor of 5 to 20, depending on the size of the system. Finally, they show that the energy consumption of a GPU-based system is significantly lower than that of a traditional CPU-based system for the same computational task, thereby reducing the carbon footprint of the computations.

There are several other examples of papers regarding green algorithms, they offer solution to the challenges of energy efficiency, power management and additionally show how to improve energy consumption by good programming practices. [100] present various techniques to achieve energy-efficient and environmentally-friendly computing for big data and machine learning. These include hardware optimization, energy-efficient algorithms, and data management strategies. The article also covers case studies and experimental results that demonstrate the effectiveness of the proposed techniques. In [101] the authors discusses the energy consumption and memory usage trade-off in sequential pattern mining on GPUs. The authors propose a technique that uses a data-driven approach to optimize the memory usage and energy consumption trade-off in sequential pattern mining on GPUs. [102] proposes a zonal-based algorithm to enhance the battery life of mobile devices in spectrum shared networks using device-to-device (D2D) communication. The algorithm, proposed by the authors, partitions the network into zones and assigns communication tasks to devices in each zone based on their energy levels and communication requirements. The authors show how this algorithm can significantly increase the battery life of mobile devices, by up to 75% compared to traditional methods, in spectrum shared networks.

Finally, there are other four relevant articles that provide valuable insights into different aspects of green computing and offer solutions to overcome the challenges associated with achieving energy efficiency and sustainability in computing: "*Efficient duality-based subsequent matching on time-series data in green computing*" by Ihm et al. [103] proposes an efficient algorithm for subsequent matching on time-series data in green computing, which can reduce energy consumption and improve performance. "*Green Code*" by Javier et al. [104] provides a comprehensive guide on writing energy-efficient code for high-performance computing, discussing various techniques and tools for achieving energy efficiency in code. "*Challenges in green computing for energy-saving techniques*" by More and Ingle [105] discusses the challenges associated with implementing energy-saving techniques in green computing and proposes solutions to overcome these challenges. "*Green Computing, Green Software, and Its Characteristics: Awareness, Rating, Challenges*" by Kern [106] provides an overview of green computing and green software, discusses their characteristics and challenges, and proposes a rating system for green software.

V. Discussion

The present study aimed to conduct a survey on green computing, with a focus on identifying trends, themes, and gaps in the research. The survey was conducted using several online databases, including Publish or Perish, IEEE Xplore, Scopus, and Web of Science. Relevant keywords, such as green computing; sustainable computing and energy-efficient computing, were used to identify articles. A total of 74 articles were identified, and all the articles highlighted the importance of sustainability in computing systems. The articles were published between 2008 and 2022, with the majority of the publications occurring in the last 5 years. This suggests a growing interest and focus on green computing among researchers in recent years.

The articles were analysed to identify key themes and topics that emerged in the research. One of the notable findings was that 14 articles focused on green algorithms. These articles explored ways to develop algorithms that are energy-efficient and can reduce the carbon footprint of computing systems. Green algorithms are an important area of research in green computing, as they can significantly reduce energy consumption and promote sustainability.

Another key theme that emerged from the survey was the multidisciplinary nature of research in green computing. The articles were contributed by researchers from various fields, such as computer science, engineering, and environmental science. This multidisciplinary approach is essential for addressing the complex challenges of achieving sustainable computing systems. Despite the growing interest in green computing, the survey also revealed several gaps in the research. For example, there is a need for more studies on the economic viability and scalability of green computing solutions. Additionally, there is a need for more research on the social and ethical implications of sustainable computing, such as the impact of computing on the environment and society.

Table I presents an overview of the areas covered in the 74 articles analysed in this survey on green computing. It is divided into 33 categories. The table provides a useful summary of the distribution of articles across these categories, which can help to identify the most significant research areas in green computing. In addition, Figure 5, on the other hand, shows the ten most commonly used keywords. The pie chart provides a quick and easy-to-understand visual representation of the frequency of these terms, with the largest slice of the pie representing the most frequently used term. The keywords that appear most frequently in the articles are green computing, energy efficiency, cloud computing, green algorithm, energy, energy consumption, internet, energy optimization, cloud, virtualization. These keywords highlight the main areas of focus in green computing research, such as the development of more energy-efficient hardware and software, the use of renewable energy sources to power computing systems, and the implementation of sustainable practices in data centres and other computing facilities. Overall, Table I and Figure 5 provide valuable insights into the areas and keywords that are most prominent in the field of green computing.

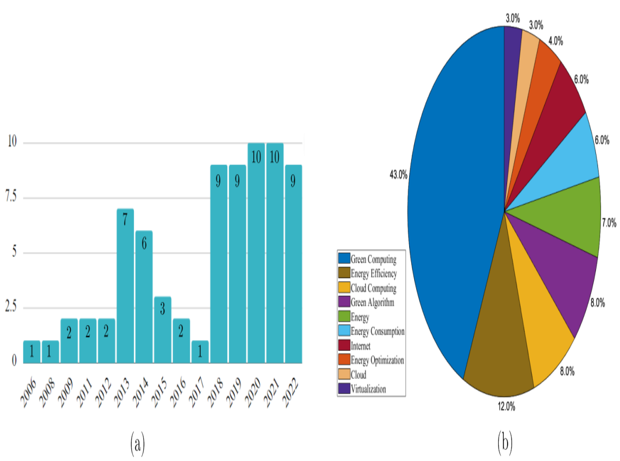

Fig. 5. Pie chart showing the top 10 most cited keywords in the 74 articles on green computing identified in the survey

TABLE I

OVERVIEW OF THE 74 ARTICLES IDENTIFIED IN THE SURVEY ON GREEN COMPUTING, HIGHLIGHTING KEY THEMES.

Area	Articles
Agriculture	[77]
Android	[40]
Autonomic green computing	[69], [70]
Bibliometric	[72]
Big data	[100]
Bioinformatics	[37]
Carbon footprint	[30], [35]–[37], [41], [45]
Cloud computing	[36], [50]–[57]
Data centre	[17], [57], [93], [94], [101], [105]
Dark Silicon	[73]
Education	[46]–[49], [76]
Energy Consumption	[43]
FPGA	[68]
Factors models	[86]
Graphic processing units (GPUs)	[99], [101]
Green Algorithm	[30], [94], [95], [97]–[106]
Hardware	[36], [78], [80], [82], [83], [101]
Internet of Things	[58]–[64]
IT sectors	[36], [44], [81]
Machine Learning	[100]
Meta-heuristic	[75]
Mobile computing	[34], [40]
Molecular Phylogenetics	[87]
Multi-label classification	[85]
Multigranularity	[92]
Near-threshold voltage design	[78]
OLED-based displays	[88]
Piezoelectric	[90]
Server forms	[91]
Sustainable design	[39]
UAVs	[89]
VM management approach	[74], [97]
Wireless networks	[65]–[67] [68], [97], [98], [102]

A. Future Directions

The concept of circuit elements with memory has the potential to revolutionize the field of green computing by significantly reducing energy consumption and improving the performance of computing systems [107]–[109]. By incorporating the principles of memfractance, researchers can design more energy-efficient computing devices that have the ability to remember previous states and adapt to changing environmental conditions. Furthermore, the potential for memfractance to reduce the energy consumption of computing systems by exploiting memory effects in circuit elements has been widely recognized, and future research in this area is likely to have significant implications for the development of sustainable and energy-efficient computing systems.

In addition to the development of energy-efficient computing devices, memfractance has the potential to be applied to other areas of green computing research. For instance, the principles outlined in [107] could be used to develop sustainable hardware designs and algorithms that reduce energy consumption and carbon footprint in computing systems. Future research in this area could lead to the development of more effective and sustainable solutions for reducing the environmental impact of computing systems. Overall, the potential of memfractance in advancing the development of sustainable and energy-efficient computing systems is immense, and future research in this area is likely to have a significant impact on the green computing industry.

VI. CONCLUSION

We presented a detailed study about green computing. This work provides a valuable reference to guide some inexperienced researchers and also contributes to encourage a conscious electronic device usage. Due to the significant environmental impact of computing systems, green computing was presented as a key aspect to be considered during computing implementation. The evaluated papers found in literature has showed how the adoption of this technique can reduce the carbon footprint in computing systems. Despite the good results applications found in those papers, greater awareness and education are required to encourage sustainable computing practices and to address the effects of climate change. Innovative solutions such as green algorithms and virtualization security assurance architectures will be the keys to achieve a greater result in optimization and energy efficiency fields, leading to enhance sustainability of computing systems.

Beyond the usage of green algorithms, changing in the common computer architectures and adoption of optimization process, the authors strongly encourage the adoption of practices that aims to switch to devices made from non-toxic materials, to the usage of renewable energy to power servers and data centres and to safe disposal/recycling of the old electronic devices. Futures works could approach the effect of adopt this practices combined with green algorithms, optimization process and computational architecture review. Additionally, by incorporating memory elements into circuit design, it may be possible to reduce energy consumption and improve performance in computing systems. In the future, further research on memfractance could lead to the development of more energy-efficient computing devices and systems.

ACKNOWLEDGEMENT

This material is based upon works supported by Maynooth University via a John and Pat Hume Doctoral (WISH) for Thalita Nazaré and Science Foundation Ireland (SFI) for Josefredo Gadelha and Erivelton Nepomuceno under contract number SFI/21/FFp-P/10065.

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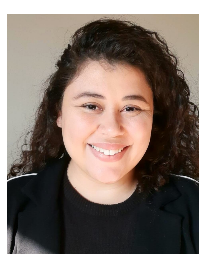

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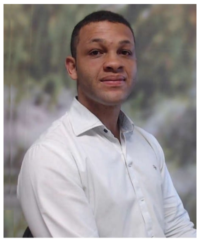

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