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Improving cloud/edge sustainability through artificial intelligence: A systematic review

Belen Bermejo *, Carlos Juiz

Computer Science Department, University of the Balearic Islands, Spain

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ABSTRACT

In recent years, the increase in the use of services in cloud, fog, edge, and IoT ecosystems has been very notable. On the one hand, environmental sustainability is affected by this type of ecosystem since it can produce a large amount of energy consumption which translates into CO2 emissions into the atmosphere. On the other hand, due to the COVID-19 pandemic, the use of these ecosystems has increased considerably. Thus, it is necessary to apply policies and techniques to maximize sustainability within these ecosystems. Some of these policies and techniques are those based on artificial intelligence. However, the current processing of these policies and techniques can also consume a lot of resources. From this perspective, this article aims to clarify whether the sustainability of cloud/fog/edge/IoT ecosystems is improved by the application of artificial intelligence. To do this, a systematic literature review is developed in this paper. In addition, a set of classifications of the analyzed works is proposed based on the different aspects related to these ecosystems, their sustainability, and the applicability of artificial intelligence to improve them.

1. Introduction

For several years now, the cloud/fog/edge ecosystems, together with the IoT, have been evolving both in their characteristics and in the amount of information and associated devices that are handled. Cloud-hosted datacenters have increased demand for computing and storage due to the increase in all these devices. In addition, the application of the IoT to such diverse fields, ranging from smart cities to smart agriculture, makes the dynamism of ecosystems increasingly difficult to manage. Nevertheless, the fact that the cloud/fog/edge/IoT environment is becoming more and more dynamic and complex means that the power consumption of the associated devices increases and, in turn, their energy consumption.

Therefore, in the last years, it has been necessary to include techniques based on artificial intelligence within the management of these ecosystems to increase their sustainability of these ecosystems. In this case, we must not understand sustainability only from an energy point of view, but it must also be taken into account from the point of view of temperature, CO2 emissions, and any other metric that is necessary.

The main objective of this work is to provide researchers in this field with a review of how Artificial Intelligence (AI) policies and techniques have contributed to improving sustainability in the cloud, edge, fog, and IoT ecosystems. Therefore, the research questions to be answered are:

- RQ1: How have the applications and contributions of AI improved the sustainability of cloud/fog/edge/IoT environments?
- RQ2: What are the future research directions and open perspectives in AI applied to cloud/edge to improve the sustainability of cloud/fog/edge/IoT environments?

This work is divided into the following sections: in Section 1 the research's context and the research question are exposed. Then, in Section 2 the related concepts regarding the research were exposed. The previously developed systematic reviews were explained in Section 3. From the gaps detected in Section 3, we depicted in Section 4 the followed methodology to perform the systematic review. In Section 5, the classification of the analyzed works is proposed. After that, all the analyzed works are explained in Section 6. Then, in Section 7, the main results are discussed. To finish, we conclude with the more important findings and future work in Section 8.

* Corresponding author.
E-mail addresses: belen.bermejo@uib.es (B. Bermejo), cjuiz@uib.es (C. Juiz).

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2. Background

In this section, the main concepts regarding the cloud, fog, edge, and IoT, together with sustainability and artificial intelligence are depicted.

2.1. Cloud/fog/edge/IoT computing

Since the appearance of cloud computing, various definitions have emerged in this regard. According to the National Institute of Standards and Technology (NIST), Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction. Also, the cloud can be defined as a computing paradigm for providing anything as a service that can be accessed conveniently, ubiquitously, across the network, dynamically, and on demand. Moreover, the cloud can be configured with minimal interaction with the service provider; and are elastic and metered on a pay-per-use basis [22] [13].

As the use of cloud services has become more popular, together with the increase in the number of devices with Internet access, new computing paradigms have emerged. Considering the heterogeneity of devices and the advances in communication networks, fog computing is an extension of the cloud but close to things (sensors, terminals, phones, etc.). Fog computing is a paradigm with limited capabilities such as computing, storing, and networking services in a distributed manner between different end devices and classic cloud computing. Moreover, the fog expands the cloud computing model to the edge of the network. Although the fog and the cloud use similar resources (networking, computing, and storage) and share many of the same mechanisms and attributes (virtualization and multi-tenancy). The main benefits of fog computing are providing greater business agility, supporting real-time services with very low latency, geographical and large-scale distribution, lower operating expense, flexibility and heterogeneity, and scalability [9].

In the same manner, edge computing contributes a new concept to the computing landscape. It brings the service and utilities of cloud computing closer to the end user and is characterized by fast processing and quick application response time. Edge computing directs computational data, applications, and services away from cloud servers to the edge of a network. This paradigm is characterized in terms of high bandwidth, ultra-low latency, and real-time access to network information that can be used by several applications [43].

The Internet of Things (IoT) can be defined as a global infrastructure for the information society enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies [72]. Besides, the IoT describes physical devices such as sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks.

As we can see, a new computing paradigm has been appearing, and computing and storage capacity has been decentralized, moving more and more towards actuator devices (such as sensors or mobile phones). In this way, the terminals are closer to the data and processing devices necessary to provide their services.

Nevertheless, the fact that computing and storage are becoming more and more distributed generated an overload in the orchestration of this ecosystem. In this way, more efficient resource management policies are required, as of course, energy management.

2.2. Sustainability

Nowadays, sustainability is one of the main concerns in IT. Sustainability can be seen from various points of view, from the manufacture of the devices to their withdrawal, through their use, and all their associated services. Of course, the manufacture and removal of technological devices produce pollution and an environmental impact. However, their use of Internet services generated much more pollution and electricity consumption. That more than 20% of the budget of large technology companies is allocated to energy expenditure [39].

The increase in energy consumption is mainly due to the increased use of cloud services along with the Edge, Fog, and IoT ecosystems. It is estimated that more than 7% of global CO2 emissions come from IT. Specifically, 45% of those emissions are caused by the datacenters that support cloud ecosystems (along with everyone else).

Due to this trend, a lot of research work related to improving sustainability in IT has been performed in the past. These works range from improving the design of devices at a physical level, such as establishing policies for energy management. Due to the complexity of finding and adapting policies to each of the ecosystems, artificial intelligence has been introduced in recent years to improve this aspect.

It is important to highlight that sustainability could be considered also from the power consumption point of view, the CO2 emissions, the temperature, and any other metric related to the environmental impact. For all of these, this work aims to study how artificial intelligence has contributed to improving sustainability in the cloud, edge, fog, and IoT ecosystems.

2.3. Artificial intelligence

Artificial intelligence (AI) can be defined as an area of study in the field of computer science concerning the development of computers able to engage in human-line through processes such as learning, reasoning, and self-correction. Moreover, artificial intelligence is the study of techniques to use computers more effectively by improved programming techniques [48].

Many problems in AI can be solved theoretically by intelligently searching through many possible solutions. Traditionally, reasoning can be reduced to performing a search. Planning algorithms search through trees of goals and subgoals, attempting to find a path to a target goal, a process called means-end analysis. Robotics algorithms for grasping objects use local searches in configuration space.

However, artificial intelligence began to have an application in the area of computing, and especially in everything related to cloud services when the demand for these services was growing exponentially. The allocation of computing resources to different users can be treated as a traditional optimization problem. That is, all the classic techniques can be applied to the current computing ecosystem. Even these techniques have been improved, giving rise to machine learning and deep learning [32].

3. Related work

Nowadays, we are in the third wave of AI, after huge expectations on the previous two occasions. Regarding, cloud/edge sustainability we may review which is the situation in this last AI era.

In [7] authors presented a survey on the prominent computing paradigms in practice highlighting the innovation from the fusion between machine learning and the evolving computing paradigms. That is, the mentioned research work is focused on cloud, edge, and fog paradigms, together with machine learning. However, the main gap in this research work is that sustainability is not considered.

In the same manner, in [66] authors deal with various software and hardware design, novel architecture and framework, specific mathematical models, and efficient modeling-simulating for advanced IT-based future sustainable computing. In the mentioned paper, the IoT and smart cities are considered, together with sustainability. Nevertheless, sustainability is not considered from the energy and power consumption point of view.

In addition, in [74] authors provided a review of the machine learning-based computation offloading mechanism in the mobile edge computing environment in the form of classical taxonomy to identify the contemporary mechanism. Mobile edge computing is the application field of the mentioned paper. However, sustainability was not considered in the mentioned paper.

Regarding edge computing, in [29] authors provide a comprehensive snapshot of the current edge computing landscape, with a focus on the application perspective. In the mentioned paper, artificial intelligence and sustainability are not considered. In addition, in [57] authors provide a comprehensive review of the smart grid systems, based on IoT and edge computing. In the same manner, as in the previous paper, artificial intelligence and sustainability are not considered. Another work regarding edge computing is [34]. In this work, the authors introduce the concepts, backgrounds, and pros and cons of edge computing, explaining how it operated and its structure hierarchically with artificial intelligence concepts. The main gap in this work is that sustainability is not considered.

Moreover, in [59] authors provided a review of the main techniques that guarantee the execution of machine learning models of hardware with low performance in the IoT paradigm, paving the way for the Internet of Conscious Things. However, the authors did not consider sustainability. Besides, in [44] a complete picture of energy efficiency in cloud computing is provided. The authors also classified heuristics-based optimization methods and dynamic power management techniques. The survey showed the research trends based on regions, journals, conferences, etc. in the domain of energy efficiency in cloud computing. In the same manner, sustainability is not considered from the power consumption point of view.

In [20], the authors explored the literature identifying the problems, categorizing the challenges, and exploring how simulation and machine learning can improve computational sustainability. Also, the authors considered the need to conduct a trade-off analysis to determine when to apply for simulation and machine learning benefits. In this paper, sustainability is considered just in the machine learning field.

In [16] authors conduct an extensive survey of an end-edge-cloud orchestrated architecture for flexible AIoT systems. In the same manner, as in previous papers, sustainability is not considered. In the same manner, in [88] an overview of the energy management solutions in the IoT to recognize the significant research trends to highlight more efficient and effective methods in IoT. Despite sustainability being considered, the mentioned paper is about dissemination and non-research focus.

Considering sustainability, in [7] authors presented the prominent computing paradigms in practice and highlights the latest innovations resulting from the fusion between machine learning and the evolving computing paradigms. In the mentioned paper, machine learning and sustainability is considered in the cloud, edge, and fog field. The main gap in the mentioned paper is that sustainability is considered from a very wide overview.

In [64] authors presented a structured review of the current research into some common AI techniques applied to load forecasting, power grid stability assessment, faults detection, and security problems in the smarts grids and power systems. Nevertheless, the main gap of this paper is that it is mainly focused on the grid computing architecture, not the cloud or the edge ones directly. In the same manner, in [69] authors presented the fundamentals of deep learning in smart grids, including energy sharing and trading.

Another field of application is smart agriculture, as [27] shows. The mentioned paper presents a review of emerging technologies for the Internet of Things based on smart agriculture. Although authors use artificial intelligence techniques considering energy efficiency, the focus is on IoT architecture, not the cloud or the edge.

Regarding the networks, in [30] authors discussed the possible ways to make software-defined networking-enabled IoT applications. Despite cloud and IoT being considered, sustainability is not a variable in this research work. In addition, in [82] a survey in 5G technologies that emphasize machine learning-based solutions is presented. The main gap in this work is the applicability, which is urban computing.

Regarding the 6G network, in [3] authors provide a comprehensive survey and an inclusive overview of Intelligence Edge Computing (IEC) technologies in 6G focusing on main up-to-date characteristics, challenges, potential use cases, and market drivers. The main gap in the mentioned paper is that sustainability is not considered.

In [35] authors conducted a study to which extent the IT community is conscious about energy evaluation of their hardware and software implementations, and whether they are in line with sustainable implications toward efficient artificial intelligence and database deployments. The main gap in this paper is about its purpose since it is devoted to dissemination, and not research. In the same manner, in [73] authors analyzed the existing energy solutions for Green IT. Also, they classified the Green IoT energy solutions based on controlled energy consumption and energy harvesting from the ambient energy sources. As the previously mentioned paper, this is devoted to dissemination more than research. Considering the same gap, in [58] an overview of green computing is presented. Also, the authors discuss how it can be achieved, together with the applications and challenges being faced for the implementation of green clouds.

Regarding the modeling, in [4] models for Green IoT devices are presented in terms of data communication, actuation process, static power dissipation, and generated power by harvesting techniques for optimal power budgeting. Despite the sustainability being considered, artificial intelligence is not considered by the model.

Considering the state-of-the-art, to the best of our knowledge, there is not a systematic literature review attempting to study the existence of improvement of sustainability in cloud/edge environments through artificial intelligence techniques. Then, the research question to solve in this work is: How has the application of artificial intelligence improved sustainability in cloud/edge environments?

4. Methodology of the systematic review

To answer the proposed research question, a Systematic Literature Review is performed. For this, the methodology proposed by [47] is followed. First, a search in the scientific database was performed. Then, they applied a selection process to the obtained information. To finish, we classified the obtained information considering bibliometric metrics. Moreover, with this review, we attempt to answer the following operative questions:

- OQ1: What previous contributions using AI improved the sustainability in cloud/edge environments?
- OQ2: What are the future research directions and open perspectives in AI applied to cloud/edge to improve sustainability?

Table 1
Summary of an initial search.

Logical expressions	Hits
"AI" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	527
"deep learning" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	709
"machine learning" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	969
"artificial intelligence" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	933
"expert system" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	55
"intelligence" and ("cloud" or "fog" or "edge") and ("green" or "energy" or "sustainability" or "sustainable"))	1140

Table 2
Summary of an initial search.

Year	Reference
<2020	[14] [90] [70] [66] [29] [34] [44]
2020	[5] [61] [74] [19] [23] [18] [59] [63] [2] [88] [87]
2021	[50] [40] [10] [26] [7] [56] [89] [57] [21] [85] [49] [20] [3] [38] [16] [41] [80] [64] [76] [68] [27] [51] [84] [53] [12] [35] [46] [73] [33] [79] [4] [71] [81] [15] [24] [65] [55] [82] [52] [28] [78] [8] [77] [58] [45] [30] [17] [67] [86] [69] [11] [37] [1] [62] [6] [31]
2022	[42] [54] [36] [25] [83] [75]

To answer the OQ1, we propose a taxonomy of the previous contributions in the AI field, aiming to improve sustainability in cloud/edge environments. The set of previous works will be classified by different criteria. Besides, to answer the OQ2, an analysis of the obtained data is performed, together with the current research gaps and future research lines.

4.1. Search process

The first step is searching the current research works in the scientific databases. Google Scholar, Science Direct, and IEEEXplore were selected as the most suitable databases for our field of study.

Moreover, the identified keywords for this search are AI, CLOUD, FOG, EDGE, GREEN, ENERGY, SUSTAINABILITY, and SUSTAINABLE. Since the term Artificial Intelligence has several variations in the literature, we also add the following keywords: DEEP LEARNING, MACHINE LEARNING, ARTIFICIAL INTELLIGENCE, EXPERT SYSTEM, and INTELLIGENCE.

Considering that we attempt to study the impact of AI on the sustainability of cloud/edge environment, we built the logical expressions shown in Table 1, obtaining a total of 4333 research works.

4.2. Selection process

The second step is the selection of the aligned research works from the initial pool (the previous 4333 ones). First, we selected the research works for 2022. Then, we removed all the duplicated works coming from the fact of using several synonyms of the "AI" term.

After removing the duplicated papers, a set of 198 papers was obtained. Then, we defined a filter for being applied to the abstracts. This filter attempts to determine if the paper contributed to the improvement of sustainability in cloud/edge/fog environments. If not, the paper was discarded. As a result, we obtain a total of 82 papers to be considered in this review.

4.3. Bibliometric information

The selected 82 papers were analyzed in a bibliometric way, obtaining useful information, as the publication year (see Table 2). Since 2020 is an inflection point in these research works, we divided the time spectrum into two blocks: before 2020 and after that. As Fig. 1 shows, there was an increment in the research works previous to 2021. Besides, 2021 is the one with more published research papers. Besides, from the beginning of 2022, the number of research papers has been increasing.

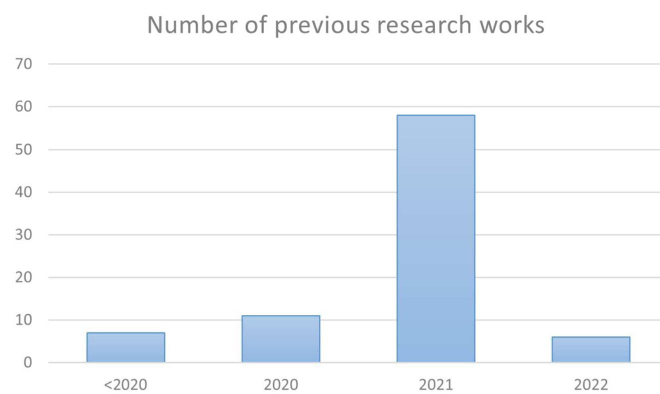

Fig. 1. Distribution of the research works by year.

Regarding the nature of the published works, 66 of them were published in journals, 14 of them were published in conferences and 2 were doctoral theses.

5. Proposed classification

In this section, the classification of the research works considering different features is shown. Since this research work aims to study the impact of AI on sustainability in a cloud/edge environment, the following features need to be considered: the architectural layer (edge, fog, and cloud), the AI methodologies and techniques, the sustainability issues, the application field and the aim of the solution.

5.1. From the ground to the sky

In this classification, we considered the Sky Computing definition, which is a metaphor to illustrate a layer above cloud computing, because such dynamically provisioned distributed domains [60]. Computing paradigms have evolved a lot in recent years. We have gone from having computers that were not connected and operated in isolation, to having fully interconnected parallel systems which access computing and storage services through the Internet. Cloud Computing is the most important computing paradigm, which plays an essential role in our daily lives. How-ever, some

Table 3
Papers classified from the ground to the sky.

	Reference
Cloud	[40] [14] [42] [90] [7] [56] [85] [44] [38] [36] [64] [84] [53] [2] [35] [33] [71] [77] [58] [30] [17] [86] [69]
Fog	[42] [90] [7] [85] [49] [41] [80] [36] [35] [33] [81] [15] [37]
Edge	[50] [42] [10] [26] [7] [61] [74] [29] [57] [85] [34] [19] [23] [18] [59] [49] [3] [41] [36] [25] [33] [79] [65] [52] [28] [45] [11] [31]
IoT	[26] [5] [89] [21] [19] [49] [54] [16] [41] [76] [68] [27] [51] [12] [46] [73] [88] [4] [87] [81] [24] [55] [82] [52] [78] [8] [83] [75] [67] [11] [37] [1] [62] [6] [31]

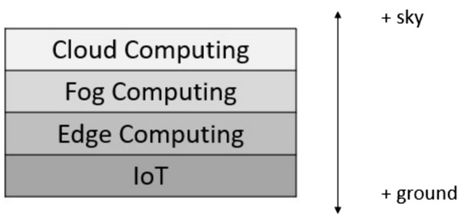

Fig. 2. From the ground to sky architecture.

more computing paradigms have emerged, due to the great popularity of services on the Internet and the huge increase in their use. These new paradigms are Fog Computing, Edge Computing, and IoT. Furthermore, these computing paradigms can be combined to solve a specific problem. For example, a challenge in a smart city can be faced by combining cloud computing and IoT.

Therefore, we can focus on the combination of the different computing paradigms, the idea of Sky Computing arises as a metaphor (see Fig. 2). At the lowest level is the paradigm closest to devices, the IoT. The next higher level is Edge Computing, followed by Fog Computing and Cloud Computing. As levels go up in the Sky Computing model, processing and storage capacity increases, and interaction with devices decreases.

Considering the above and the increase in the use of a combination of different computing paradigms, in this SLR the different works have been classified according to the paradigms in which they are framed.

In Table 3 the articles classified by computing paradigms are shown. Moreover, Table 4 shows the different works based on the combination of the different working paradigms. From these two tables we can observe the following data:

- Cloud 24/82 → 29,26%
- Fog 14/82 → 17,07%
- Edge 29/82 → 35,36%
- IoT 29/82 → 35,36%

From the previous data, we can appreciate that most of the research works are related to the Edge paradigm and the IoT. This fact is because they are the layers closer to the final devices or workstations, and therefore to a particular problem. However, the Fog and Cloud paradigms are mainly based on executing the load contained in servers.

Therefore, the dynamism of the problems is usually less.

In addition, we can observe that the same research article can deal simultaneously with several computing paradigms, as can be seen in Table 4. Of all the possible combinations between the different paradigms, the ones that appear the most are:

- Cloud + Fog
- Fog + IoT
- Edge + IoT
- Fog + Edge + IoT

The Cloud + Fog combination is present in the 2,53% research works, the Fog + IoT represents also 2,53%, the Edge + IoT corresponds to 6,32%, the Fog + Edge + IoT represents 2,53% and the Cloud + Fog + Edge regards the 7,59% of them. Regardless of the values, different computing paradigms are beginning to be combined to solve problems. In addition, paradigms closer to the sky and paradigms closer to the ground are usually combined.

However, the most widely used combinations of paradigms include the Edge Computing and IoT layers. As we mentioned previously, the problems that are faced in these layers are more specific due to the dynamism of the involved devices.

5.2. Classification of the AI methodologies and techniques

The second classification we proposed in this work is from the artificial intelligence techniques' point of view. For this, we defined a set of techniques that will be considered in this work such as optimization-based techniques, machine learning, deep learning, artificial neural networking, prediction model, heuristic-based techniques, Bayesian learning frameworks, multi-agents systems, AI models, distributed AI and the combination of the previous techniques. Before showing the classification, the previous AI techniques are defined as follows:

- Optimization-based techniques are used in many areas of study to find solutions that maximize or minimize some study parameters, such as minimizing costs in the production of a good or service, maximizing profits, minimizing raw materials in the development of a good, or maximizing production.
- Machine learning is a field of inquiry devoted to understanding and building methods that "learn". That is, methods that leverage data to improve performance on some set of tasks. Machine learning algorithms build a model based on sample data to make predictions or decisions without being explicitly programmed to do so.
- Deep learning is a class of machine learning algorithms that uses multiple layers to progressively extract higher-level features from the raw input. Deep learning methods are based on artificial neural networks, being the "deep" adjective refers to the use of multiple layers in the network.
- Artificial neural networking is a computational model that mimics the way nerve cells work in the human brain. They use learning algorithms that can independently make adjustments as they receive new input.
- A prediction model is a mathematical process used to predict future events or outcomes by analyzing patterns in a given set of input data.
- Heuristic-based techniques are approaches to problem-solving that uses a practical method or various shortcuts to produce solutions that may not be optimal but are sufficient given a limited timeframe or deadline.
- The Bayesian learning framework is a common supervised learning algorithm. Bayesian learning is used in deep learn-

Table 4
Papers are classified by the combination of different paradigms.

Reference	Cloud	Fog	Edge	IoT	Reference	Cloud	Fog	Edge	IoT
[22]			X		[6]				X
[40]	X				[36]	X	X	X	
[14]	X				[25]			X	
[42]	X	X	X		[64]	X			
[90]	X	X			[76]				X
[10]			X		[68]				X
[26]			X	X	[27]				X
[7]	X	X	X		[51]				X
[5]				X	[84]	X			
[56]	X				[53]	X			
[89]				X	[12]				X
[61]			X		[2]	X			
[74]			X		[35]	X	X		
[29]			X		[46]				X
[57]			X		[73]				X
[21]				X	[88]				X
[85]	X	X	X		[33]	X	X	X	
[34]			X		[79]			X	
[19]			X	X	[4]				X
[23]			X		[71]	X			
[18]			X		[87]				X
[59]			X		[81]		X		X
[44]	X				[15]		X		
[49]		X	X	X	[24]				X
[3]			X		[65]			X	
[54]				X	[55]				X
[38]	X				[82]				X
[16]				X	[52]			X	X
[41]		X	X	X	[28]			X	
[80]		X			[78]				X
[75]				X	[8]				X
[67]				X	[77]	X			
[86]	X				[58]	X			
[69]	X				[83]				X
[11]			X	X	[45]			X	
[37]		X		X	[30]	X			
[1]				X	[17]	X			
[62]				X	[31]			X	X

ing, which allows deep learning algorithms to learn from small datasets.

- A multi-agent system is a computerized system composed of multiple interacting intelligent agents. They can solve problems that are difficult or impossible for an individual agent or a monolithic system to solve.
- AI models, in general, represent an abstraction of reality that could be evaluated in a different condition from the real ones. In this work, the AI models were used to assess an AI-based system without the necessity of having it physically.
- Distributed Artificial Intelligence is based on classical distributed computing. However, distributed computing devices incorporate an AI technique or method to work more efficiently.
- A set of AI techniques is a combination of different techniques of AI that could be considered. All of these techniques were explained previously. For example, a problem could be solved using a machine learning technique together with an optimization function.

In Table 5, the distribution of research works, and artificial intelligence techniques are shown. We can see the most used techniques are machine learning, deep learning, those based on optimization, and solutions based on a set of artificial intelligence techniques.

From the information shown in Table 5, we can observe that machine learning, deep learning, and optimization-based techniques are being more widely used because deep learning allows solutions to problems to be found much more efficiently. On the other hand, the fact of using different artificial intelligence techniques is due to the diversity of the problems to be faced. For most problems, it is necessary to combine different techniques and thus accommodate the heterogeneity and particularities of each problem to be solved.

However, the fact of combining different techniques makes the management process of the problem to be solved more complex. Also, the set of techniques is applied in the form of a sequential process, where the result obtained from applying one technique is used as input to the next one.

5.3. From the sustainability point of view

Since the aim of this paper is to review how AI impacted the cloud/edge architecture from the sustainability point of view, we classified the research works considering the different ways of considering sustainability.

That is, we could consider metrics such as energy consumption, power consumption, energy efficiency, CO2 emissions to the atmosphere, the temperature of servers and datacenters, and a combination of the exposed metrics.

As we can observe in Table 6, most of the research works regard the energy consumption and the energy efficiency of servers and datacenters. It is important to note that energy consumption (kWh) is the amount of power consumed (Watts) during a certain period. Therefore, it is one of the most interesting metrics in sustainability, where the goal is to minimize energy consumption.

On the other hand, energy efficiency relates to the amount of energy that is consumed in the system in carrying out its tasks in

Table 5
Distribution of research works by artificial intelligence techniques.

	Reference
Optimization-based techniques	[40] [14] [42] [70] [5] [85] [34] [49] [84] [88] [87]
Machine learning	[42] [7] [66] [61] [74] [63] [20] [38] [25] [12] [2] [4] [81] [55] [82] [8] [77] [45] [30] [1] [62] [6]
Deep learning	[50] [26] [21] [12] [15] [24] [28] [78] [58] [69] [11]
Artificial Neural Networking	[90] [18] [68] [27] [51] [52]
Prediction model	[46] [65]
Heuristic-based techniques	[44]
Bayesian learning framework	[10]
Multi-agent systems	[23]
AI models	[19] [16]
Distributed Artificial Intelligence	[61]
Set of AI techniques	[56] [89] [29] [57] [3] [54] [41] [64] [76] [53] [35] [73] [33] [79] [71] [83] [17] [75] [67] [86] [37] [31]

Table 6
Research works classified by sustainability metrics.

	Reference
Energy consumption	[50] [10] [70] [5] [57] [59] [41] [36] [89] [76] [68] [53] [2] [35] [46] [73] [88] [79] [4] [15] [24] [65] [52] [58] [67] [69] [11] [1] [62] [31]
Power consumption	[14] [90] [44] [16] [64] [35] [88]
Energy efficiency	[42] [7] [66] [56] [89] [61] [74] [85] [49] [20] [3] [54] [38] [80] [25] [27] [84] [12] [33] [87] [81] [55] [82] [78] [8] [83] [17] [86] [37] [6]
CO2 emissions	[40] [26]
Temperature	[45]
Metrics' combination	[29] [21] [34] [19][23] [18] [63] [51] [71] [28] [77] [30] [75]

proportion to that originally injected. In this case, the aim Will be to maximize energy efficiency. If the energy efficiency is maximum, it means that the energy that is injected into the system will be used only in carrying out the tasks of the system. However, energy efficiency is never maximum, since within the system there are power losses in devices such as air ventilation.

In addition, nowadays 20% of the budget of large companies is allocated to electricity waste [39], having lower energy consumption and greater energy efficiency is also reflected in a decrease in the monetary cost of electricity.

In addition, in this work, we have a special interest in the relationship between sustainability and artificial intelligence techniques and methods. For this, in Table 7 the relationship between both variables through the work carried out is shown.

We can see that there are not many jobs to reduce power consumption, CO2 emissions, and temperature using artificial intelligence. However, to reduce energy consumption, increase energy efficiency or combine different sustainability metrics, the most used AI techniques are machine learning, deep learning, and optimization-based techniques.

5.4. From the area of application

Another type of classification for the research works related to sustainability in the cloud/edge and AI is considering- the area of application. In each of these fields of application, some devices should be managed at an energy level, such as servers, sensors, communication networks, etc.

As we can see in Table 8, datacenters are where there are more jobs concerning improving sustainability through artificial intelligence. This fact is due to the high energy consumption of current datacenters, which account for 7% of global CO2 emissions [39]. Therefore, it is an area where it is very interesting to work intensively.

Other application areas that have a considerable number of research works are devoted to smart cities, sensor networks, and IoT devices. These three areas have a similarity, which is their use of low-capacity computing devices and sensors.

5.5. Considering the paper nature

The last classification of research articles is based on their nature. That is if the article is a survey, a research topic review, or a proposal of new knowledge such as an algorithm, a framework, architecture, etc.

As we can observe in Table 9, most of the works carried out are surveys or review topics. This fact shows that the improvement of sustainability through AI in cloud/fog/edge environments is an important topic to be considered.

This fact could be due to stagnation in the field of study considered in this SLR. That is, at the current point of history there is difficult to improve the sustainability in the cloud/edge through artificial intelligence.

6. Research works description

In this section, we will explain the main features of the considered research works by the different sky layers (cloud, fog, edge, and IoT). It is important to note that there is a set of papers deal-

Table 7
Relation between the sustainability metrics and AI techniques.

	Energy consumption	Power consumption	Energy efficiency	CO2 emissions	Temperature	Metric's combination
Optimization-based techniques	[70] [5] [88]	[14]	[42] [85] [49] [84] [87]	[40]		[34]
Machine learning	[56] [80] [1] [62]	-	[42] [7] [66] [61] [74] [20] [38] [25] [12] [81] [55] [82] [8] [6]		[45]	[63] [77] [30]
Deep learning	[50] [15] [24] [58] [69] [11]	-	[12] [78]	[26]	-	[21] [28]
Artificial neural networking	[68] [52]	-	[27]	-	-	[18] [51]
Prediction model	[46] [65]	-	-	-	-	-
Heuristic-based techniques	-	[44]	-	-	-	-
Bayesian learning framework	[10]	-	-	-	-	-
Multi-agent systems	-	-	-	-	-	[23]
AI models	-	[16]	-	-	-	[7]
Distributed Artificial Intelligence	[36]	-	-	-	-	-

Table 8
Research works classified by the area of application.

	Reference
E-health	[21] [80] [36] [77]
Datacenters	[50] [14] [42] [70] [7] [66] [56] [61] [44] [20] [47] [5] [19] [40] [10] [89] [80] [24] [55]
Application layer	[44] [88] [49] [52]
Servers	[43] [56] [53]
Smart agriculture	[90] [87] [50] [86]
Smart cities	[74] [57] [16] [18] [33] [81] [8] [17] [11] [37]
Smart buildings	[21] [38]
Mobile computing	[39] [59] [28]
Cloud gaming	[13]
Cloud networks	[72] [82]
Industry 5.0	[32] [76] [79] [78]
Smart grid	[20] [23] [41] [45]
Sensor networks	[7] [64] [69] [4] [26] [46]
IoT devices	[27] [14] [85] [68] [84] [65] [67] [1]
Green IT companies	[35] [89]
5G/6G networks	[58] [12]
Blockchain	[63] [2] [71]
Cybersecurity	[51] [77]

ing with different layers of the sky. In these cases, we will not repeat the content in the different layers of the sky.

6.1. From the cloud computing layer

The sustainability from the cloud gaming point of view is considered in [40]. In this work, the authors found seven criteria that affect the Quality of Experience in gaming. They examined these criteria against three pillars of sustainability. Authors depict that cloud gaming can become a disruptive innovation in the gaming disruptive innovation is the gaming industry by making gaming more sustainable.

Since cloud computing has become a fast-emerging technology, authors discussed in [14] various efficient energy-saving Green IT methods. The discussed techniques were the use of renewable energy, the inclusion of nano datacenters, the use of energy-efficient storage, the reduction of CPU power dissipation, using an advanced clock gating, the reduction of cooling requirements, the saving strategy of hardware temperature control, the server consolidation, the energy savings for computer architecture and compiling technology, the energy saving strategy of application software power, energy saving strategy of the system software, the energy saving strategy of virtual machines manager, the live migration of virtual machines, the energy saving strategy of network environment and

Table 9
Research works are classified by their nature.

	Reference
Survey	[7] [66] [59] [44] [20] [88] [27] [30] [73] [58] [14] [5] [23] [87] [89] [85] [49] [80] [46] [24] [52] [45]
Taxonomy proposal	[43]
Particular framework proposal	[3] [71] [78]
Methodology proposal	[74] [2] [51] [84]
Guidelines proposal	[32]
Algorithm proposal	[72] [39] [48] [34] [16] [70] [79]
Metrics review	[22]
Topic review	[13] [57] [82] [47] [19] [18] [10] [26] [21] [38] [41] [80] [76] [12] [33] [81] [65] [28] [8] [17] [67] [86] [11] [37]
Strategy proposal	[9] [29]
Architecture proposal	[7] [64] [69] [90] [61] [63] [50] [15]
Model proposal	[35] [40] [53] [55] [1]
Green assessment	[4] [56] [77]
Exploration paper	[68]

the task consolidation for efficient energy consumption. In addition, the authors concluded that cloud computing is effective if the energy consumed in servers is saved.

In [90], the authors formulated the placement of DNN interference models using Mixed Integer Linear Programming. They abstracted the model as a network embedding problem in a Cloud Fog Network architecture, where power savings are introduced through trade-offs between processing and networking. Also, they study the performance of the CFN architecture by comparing the energy savings when compared to the baseline approach with the CDC.

In [42], the authors provided a novel federal classification between the cloud, edge, and fog. Also, they represented a comprehensive research roadmap on offloading for different federated scenarios. In the same manner, in [7] authors presented a survey on the prominent computing paradigms in practice highlighting the latest innovations resulting from the fusion between machine learning and the evolving computing paradigms and discusses the underlying open research challenges and prospects. In addition, in [44] authors intend to provide a complete picture of energy efficiency in cloud computing. It also classifies heuristics-based optimization methods and dynamic power management techniques. Also, the proposed survey shows the research trends based on regions, journals, conferences, etc. in the domain of energy efficiency in cloud computing. The study concluded with research issues and future research directions.

Following the surveys, in [64], a survey is presented as a structured review of the existing research into some common AI techniques applied to load forecasting, power grid stability assessment, faults detection, and security problems in the smart grid and power systems. Moreover, in [2], the survey is structured around classifying the scheduling techniques into four categories based on the type of optimization algorithm employed to generate the schedule namely mathematical modeling, heuristics, metaheuristics, and machine learning. In the same manner, in [33] authors presented the first timely and comprehensive reference for energy-efficiency recommendation systems.

Considering the bibliometric information of the research works, in [71], these data from Scopus are analyzed and visualized. This paper just considered the years from 2020 to 2022.

Regarding the review topics, in [38] authors review various clustering, optimization, and machine learning methods used in cloud resource allocation to increase energy efficiency and performance are analyzed, compared, and classified. Besides, in [7] authors presented an extended survey on the prominent computing paradigms in practice highlighting the fusion between machine learning and the evolving computing paradigms and discussing the underlying open research challenges and prospects. Moreover, in [53] authors present a comprehensive picture of the adoption trend of emerging digital technologies in the US energy sector, comparing the coverage rate of the emerging digital technologies across different occupations.

In the same manner as the previous reviews, in [35] authors conduct a newsworthy inquiry purposing to study to which extent the IT community is conscious about energy evaluation of their hardware and software implementations, and whether they are in line with sustainable implications toward efficient artificial intelligence and big data deployments. Moreover, in [58] authors provided an overview of green cloud computing and also talks about how it can be achieved. It also talks about the applications and challenges being faced in the implementation of green clouds.

In addition, in [56], the authors proposed strategies for energy efficiency and conservation in datacenters. Besides, the authors proposed an IoT infrastructure based on edge-fog-cloud computing architecture to monitor and control residential loads. In the same manner, in [36], a reference architecture is proposed which provides Artificial Intelligence as a Service over the cloud, fog, and edge using a service catalog case study containing 22 AI skin disease diagnosis services.

Considering the models, in [84] authors proposed a model that formulates the goal of optimizing energy efficiency in datacenters as a multi-objective scheduling problem, considering three important models: energy, thermal and cooling. Regarding the cloud platforms, in [77] authors presented an intelligent cloud-based platform for workers' healthcare monitoring and risk prevention in potentially hazardous manufacturing contexts.

Considering the software-defined networking, in [69] the possible ways to make software-defined networking-enabled IoT applications are discussed. Also, the authors discussed the challenges solved using the Internet of Things leveraging the software-defined network. Besides, they provided a topical survey of the application and impact of software-defined networking on the Internet of Things networks. Considering also the networks, but from the Mobile Cloud Computing perspective, in [17] authors highlighted the areas and the extent to which the edge, fog, and cloud computing technologies can support green technology and ways to increase this support.

In [86] authors discussed what needs to be considered by both policymakers and managers to exploit the use of artificial intelligence for sustainable development achievement. In this case, artificial intelligence can act as a real and meaningful enabler to achieving sustainability goals. The last research work to be considered from the cloud per- perspective is [69]. In this work, the authors presented the fundamental of deep learning, smart grids, demand response, and the motivation behind the use of deep learning. Also, they review the state-of-the-art applications of deep learning, including electric load forecasting, state estimation, energy theft detection, energy sharing, and trading.

6.2. From the fog computing layer

In [49], the authors presented a comprehensive review of edge and fog computing research in IoT. They investigated the role of the cloud, fog, and edge computing in the IoT environment. Subsequently, they covered in detail, different IoT use cases with edge and fog computing, the task scheduling in edge computing, the merger of software-defined networks (SDN) and network function virtualization (NFV), and privacy efforts. In the same manner, in [41], the authors reviewed to identify all relevant research on new computing paradigms with smart agriculture and propose a new architecture model with the combination of cloud-fog-edge.

Moreover, in [7] authors surveyed and presented the prominent computing paradigms in practice highlighting the latest innovations resulting from the fusion between machine learning and the evolving computing paradigms and discussing the underlying open research challenges and prospects. Also, in [37] authors examined the current state of mist processing and its integration with IoT, focusing on the effect of execution challenges. This review paper in addition focuses on fog structural design and upcoming IoT applications that will be enhanced with the utilization of the fog structure.

In [81], the authors explored the machine learning algorithms on the resource constraint IoT fog computing framework is the determination of the suitable machine learning classifier for reducing latency and energy levels with the usage of ambient sensors in the IoT theme. Besides, in [15] a novel method, deep learning FFT for cyber-security has been used in the proposed paper to enable attack detection in datacenters. The deep model and traditional machine learning way are evaluated in terms of performance, and distributed attack detection has been compared to the centralized diagnosing procedure.

6.3. From the edge computing layer

In [50] authors defined training efficiency as a new universal metric to assess deep learning sustainability and compare them to similar, less universal metrics. The proposed metric is based on energy consumption, deep learning, inference, recognition gradients, number of classes, universally balanced accuracy, complexity, and energy consumption. Similarly, in [26] authors explored the different aspects of the impact of the design and development of Edge-AI G-IoT systems. They provide guidelines that will help future developers to face the challenges that will arise in creating the next generation of Edge-AI G-IoT systems.

In [10], the authors proposed a Bayesian learning framework for jointly configuring the service and the Radio Access Network (RAN), aiming to minimize the total energy consumption while respecting desirable accuracy and latency thresholds. In addition, in [61], the authors focused on AI at the edge, illustrating the benefits of integrating data fusion with AI at the edge. Also, they proposed a framework for AI and data fusion at the edge, comparing the proposed framework with different architectures.

Regarding the review's topic, in [7], the authors presented a survey on the prominent computing paradigms in practice and highlight the latest innovations resulting from the fusion between machine learning and evolving computing paradigms. Also, they discussed the underlying open research challenges and prospects. In the same manner, in [74] authors provided a review of machine learning–based computation off-loading mechanisms in the Mobile Edge Computing environment in the form of classical taxonomy to identify the contemporary mechanism on this crucial topic and to offer open issues as well. In addition, a snapshot of the current edge computing landscape, with a focus on the application perspective is proposed in [29]. Moreover, in [57] authors provided a comprehensive review of the smart grid systems, based on IoT and Edge Computing. Moreover, in [59] authors provided a review of the main techniques that guarantee the execution of machine learning models on hardware with low performance in the IoT paradigm, paving the way for the Internet of Conscious Things.

Similarly, in [3] a comprehensive survey is provided. Also, the authors provided an inclusive overview of the Intelligence Edge Computing (IEC) technologies in 6G focusing on main up-to-date characteristics, challenges, potential use cases, and market drivers. In addition, in [52] authors classify technical aspects of energy harvesting management methods in sustainable urban computing concerning applied algorithms, evaluation factors, and evaluation environments.

In [34], the authors introduced the concepts, backgrounds, and pros and cons of edge computing, explaining how it operated and its structure hierarchically with artificial intelligence concepts. Also, they listed examples of its applications in various fields and finally they suggested some improvements and discusses the challenges in various fields. Besides, the goal of [11] is to provide a thorough overview of the present state-of-the-art convergence of deep learning and edge computing. It will also cover open issues such as system performance, network technology and management, benchmarking, and privacy.

From the architecture proposal point of view, in [19], the authors proposed a new architecture used to deploy edge-level microservices and adapted artificial intelligence algorithms and models. In addition, the novelty of [23] is the coupling of a wireless sensor network and a multi-agent system deployed on an edge AI-IoT architecture through Kubernetes and Docker. Also, in [18], the authors proposed scalable monitoring of poultry achieved with open hardware wireless sensors network and software. They used the Gated Recurrent Algorithm, which validated the environmental parameters.

In [25], the authors investigated the challenges of running machine learning and deep learning on edge devices in a distributed way, paying special attention to how techniques are adapted to execute on these restricted devices. Similarly, in [79], the authors investigate the edge computing solutions for the smart grid. A comprehensive review of both emerging issues and edge computing in the Smart Grid environment was discussed and explained.

Regarding the prediction models, in [65], the authors presented an energy prediction model based on the edge computing technique. They used a dataset where various environmental and energy use information has been considered. Also, they used five different machine learning classifiers to classify the prediction model and assess the prediction performance. Also, in [28], prior findings were cumulated indicating the interoperability between Internet of Things-based real-time production logistics and cyber-physical process monitoring systems. Moreover, in [45] authors attempt to answer the research questions: (1) Can an edge device produce an indoor temperature forecast? and (2) Can the ANN prediction model achieve improved accuracy compared to the other models?

6.4. From the IoT layer

Considering the review's topic, in [54] a detailed study on several prevalent and innovative IoT solutions in terms of Green IoT is performed in this paper. More specifically, the assessment and comparison of these Green IoT solutions are carried out based on their characteristics, technology used, outcomes, usability, and limitations. Besides, in [16] an extensive survey of an end-edge-cloud orchestrated architecture for flexible AIoT systems. Moreover, in [27], the authors presented a comprehensive review of emerging technologies for IoT-based smart agriculture. They began summarizing the existing surveys and describing emergent technologies for the agricultural IoT, such as unmanned aerial vehicles, wireless technologies, open-source IoT platforms, software-defined networking (SDN), network function virtualization (NFV) technologies, cloud/fog computing, and middleware platforms.

In [12], an up-to-date survey on recent energy management techniques in IoT networks. They started presenting the challenge of energy consumption in IoT networks. Besides, [52] aimed to classify the technical aspects of energy harvesting management methods in sustainable urban computing concerning applied algorithms, evaluation factors, and evaluation environments. In [37] authors examined the current state of mist processing and its integration with IoT, focusing on the effect of execution challenges. Also, this work focused on fog structural design and upcoming IoT applications that will be enhanced with the utilization of the fog structure.

The research trends and applicability of machine learning techniques, as well as the deployment of developed machine learning models for use by farmers toward sustainable irrigation management, were proposed in [1]. Besides, in [62] authors offered a short overview of artificial intelligence for sustainability, in the context of smart cities. Moreover, [6] focused on providing a comprehensive review of the techniques and strategies for making cities smarter, more sustainable- able and eco-friendly.

In [5] authors presented a low-cost platform for monitoring and helping decision-making about different areas in a neighboring community for efficient management and maintenance, using information and communication technologies. Besides, in [89] authors reflected on opinions and interpretations, and concentrated on the Green AI concepts as an enabler of the smart city transformation. In addition, in [76], the performance of the proposed architecture is evaluated in terms of qualitative and quantitative measurement.

Similarly, in [51] authors studied the architecture of wireless sensor nodes and networks oriented to complex agricultural habitat conditions. Moreover, because of the harsh environment of data collection in agricultural production sites and the higher requirements for network robustness. Besides, in [46] authors investigated the research themes on smart homes and cities through a quantitative review and identified barriers to the progression of smart homes to sustainable smart cities through a qualitative review.

In the same manner, in [68], the authors proposed a learning method to efficiently solve JORP based on branch-and-bound (BnB). Our proposed learning mechanism can intelligently imitate the branching/pruning actions of BnB and remove unlikely solutions in the search space based on the deep neural network model to improve the performance. Moreover, in [21] authors proposed a deep federated learning framework for healthcare data monitoring and analysis of IoT devices. Besides, in [19] authors proposed a new architecture used to deploy at edge level microservices and adapted artificial intelligence algorithms and models. Also, [89] highlights the fundamental shortfalls in mainstream AI system conceptualization and practice, and, advocates the need for a consolidated AI approach to further support smart city transformation. Similarly, in [81] authors explored the machine learning algorithms on the resource constraint of the IoT fog computing framework and the determination of the suitable machine learning classifier for reducing latency and energy levels with the usage of ambient sensors in the IoT theme were presented.

Regarding energy solutions, in [73], the authors analyzed the existing energy solutions for Green IoT. Also, the proposed survey will classify and present the Green IoT energy solutions into two categories, one based on controlled energy consumption and the second one relying on energy harvesting from ambient energy sources. Also, in [88], an overview of the energy management solutions in the IoT is presented. The main goal of this work was to recognize significant research trends in the field of energy management and power consumption techniques. Moreover, in [4], various energy-efficient hardware design principles, datacenters, and software-based data traffic management techniques are discussed as enablers of GIoTs. Energy models of IoT are presented in terms of data communication, actuation process, static power dissipation, and generated power by harvesting techniques for optimal power budgeting.

While smart manufacturing and intelligent manufacturing are similar, they are not identical. From an evolutionary perspective, there has been little consideration of whether the definition, though, connotation, and technical development of the concepts of smart manufacturing or intelligent manufacturing is consistent in the literature. To address this gap, [87] performed qualitative and quantitative research of the literature to compare inherent differences between smart manufacturing and intelligent manufacturing, and to clarify the relationship between both concepts.

From the renewable energy point of view, in [24], renewable energy is widely applied in energy systems to alleviate the carbon footprint. However, the instability and discontinuity of renewable generation decrease the quality of service (QoS) of edge servers. To address the challenge, a renewable prediction-driven service offloading method (ReSome) was proposed. Technically, a deep-learning-based approach is designed for renewable energy prediction.

Considering the 6G technologies, in [55] an overview of the massive IoT and 6G enabling technologies is presented. The authors discussed different energy-related challenges that arise while using fog computing in 6G enabled massive IoT. They categorized different energy-efficient fog computing solutions for IoT and described the recent work performed in these categories. Similarly, in [82], the authors provided a comprehensive survey on 5G technologies that emphasize machine learning-based solutions to cope with existing and future challenges.

Inspired by Blockchain and artificial intelligence technology, in [78] a blockchain-enabled secure framework was proposed for energy-efficient smart parking in a suitable city environment. The transport layer implements the proposed algorithm to encrypt and decrypt the parking zone data for secure communication. Moreover, [8] is focused on Big Data in the city's energy efficiency. A literature analysis is performed and returned a taxonomy of existing energy efficiency assessment models under the lens of artificial intelligence and big data. Also, the definition of a unified assessment model for artificial intelligence and Big Data energy efficiency is approached. In [67] authors provided a brief overview of enabling G-IoT-based smart cities. The work described the various characteristics of urban smart cities and how G-IoT can be enabled in these cities to provide numerous technological functionalities. Also, the use of a cloud-based framework for minimizing the use of hardware.

To achieve a sustainable next-generation IoT ecosystem and guide us towards making a healthy green planet, the authors offered an overview of Green IoT (GIoT), and then the challenges and the future directions concerning GIoT were presented in the study.

Industry 4.0 also needs to be considered. For this, in [75] the importance of industry 4.0, the industrial revolution and the scope of Edge artificial intelligence-based technologies are detailed. The notion of smart manufacturing and predictive maintenance is also discussed. A robust and versatile predictive analytic framework is proposed in this work.

7. Discussion

In this section, we will discuss the most understanding results of the review presented throughout the work will be discussed.

Considering the temporal distribution of the analyzed works, we can observe that until 2020 relevant works in this area do not begin to appear. In addition, in 2021, the number of research works related to sustainability in the cloud/fog/edge applying artificial intelligence increase drastically. This fact may be because the topic is newborn and no work has yet been developed in this regard.

On the other hand, from the point of view of the sky layers, most of the researchers are focused on the IoT and Edge layers. This fact may be due to the great variety and dynamism of the devices associated with these layers, especially small devices that have sufficient computing capacity. However, there is also a high percentage of research works focused on the cloud layer, specifically datacenters. Ultimately, all computing is held in datacenters, and these are now in the cloud.

Considering the artificial intelligence techniques used, the most used are machine learning and deep learning. It is important to consider that the spectrum of solutions is wide and using machine learning and deep learning techniques helps to cover the spectrum of solutions much more efficiently. In addition, there is a considerable percentage of work that makes use of a set of artificial intelligence techniques. In these cases, what is intended is to consider the dynamism and variety in the solutions to each problem. That is, each problem needs a specific solution. This fact can become unfeasible since generic solutions would cease to exist.

From the point of view of sustainability, most of the research works are focused on reducing energy consumption and maximizing energy efficiency. To do this, the most used artificial intelligence techniques are machine learning and deep learning. In this case, it must be considered that the energy depends on the time of use of the devices and execution of the workload, and this, in turn, depends on the dynamism of the devices that are used. In addition, these devices generate a wide range of solutions, requiring machine learning and deep learning techniques.

In the same way, if we consider the application of the work carried out, we can see that datacenters, smart cities, and IoT devices are the ones that present the most related work. Returning to previous arguments, datacenters are the last recipients of all the load generated in the cloud/fog/edge ecosystem, therefore, they should be taken into special account. In addition, IoT devices, whether they are for smart cities or not, have a high population density, thus generating great dynamism. Then, these facts should be considered.

Finally, if we considered the nature of the research works, surveys and review topics are the most dominant. This links to the first fact that we have highlighted, and it is the newborn topic. It is necessary to know the current state of the art to start generating applicable knowledge in the most general way possible.

8. Conclusions and future work

In this paper, we have summarized the last research works regarding the sustainability of cloud, edge, fog, and IoT infrastructure using artificial intelligence. We attempted to answer how artificial intelligence improved the sustainability of these ecosystems. Additionally, we have reviewed the previous works to find the gaps in the past research. Moreover, we reviewed the main concepts regarding the sustainability of cloud, edge, fog, and IoT, using artificial intelligence. We have studied the layers of the sky computing environment, the main techniques of artificial intelligence, the areas/fields of application, and the main metrics of sustainability. Also, we have included the paper's nature.

The main contribution of this work is the categorization of the related literature considering the sky layers, the artificial intelligence methods and techniques, the sustainability metrics, the area/field of application, and the paper's nature. From the different classifications, we conclude that machine learning and deep learning are the most used techniques to solve ad-hoc problems, especially in Edge and IoT scenarios. Also, energy consumption and energy efficiency are the metrics that these works attempt to optimize. Then, there is a lack of generality in the proposed solutions for improving sustainability in cloud/fog/edge/IoT ecosystems. Moreover, this paper could help other researchers to create new knowledge regarding AI and sustainability in cloud/fog/edge/IoT environments. Besides, new researchers in this field could have the basic knowledge and past contributions to following research in this area.

As a future work line, there is a set of opportunities regarding the generalization of the sustainability-improvement techniques in sky computing. It would be very useful to find methods or techniques based on artificial intelligence to improve the sustainability of cloud/fog/edge/IoT environments. The expectations of this third wave of artificial intelligence are also exposed in the case of research on cloud/fog/edge/IoT and its sustainability. In the not-too-distant future, we will have to evaluate if these expectations have been met or have been reduced as in the two previous eras.

CRediT authorship contribution statement

Belen Bermejo: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Carlos Juiz:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Belen Bermejo reports financial support was provided by University of the Balearic Islands.

Data availability

No data was used for the research described in the article.

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Dr. Belen Bermejo obtained her PhD in 2020 from the University of the Balearic Islands (UIB). Since 2016 she is assistant lecture at the computer science department of the UIB and member of the ACSIC group. She is chair of the WiE section of IEEE Spain. Her research is mainly focused on the improvement of the energy efficiency in datacenters and servers, together with the improvement of the performance of that systems, specially virtualized datacenters. Throughout her career as a researcher, she has published several papers in indexed journals, as well as numerous international conferences. She has also published several book chapters, as well as being a member of the scientific committee and organization of international conferences. Also, she has been visitor at the Newcastle University in 2017 and 2018, and at the University of Sevilla in 2022. She has been awarded in 2016 and 2020 with research and dissemination prizes. Also, she has participated in several research projects at national European level (H2020). In addition, she has participated in two European Erasmus+ K2.

Professor Carlos Juiz received the PhD degree in Informatics from the University of the Balearic Islands (UIB), Spain. Before joining the Department of Computer Science at UIB, he had several positions related to the computer systems industry. From 1990 he was Systems Analyst at Xerox, leaving this position as Senior Analyst in 1999. He was visiting researcher at the Department for Computer Science and Business Informatics, University of Vienna, in 2003 and Visiting Associate Professor at Biomedical Informatics Research, in 2011, at Stanford University. Carlos Juiz is heading the ACSIC research group (http://acsic.uib.es) and his research interest mainly focuses on performance engineering, Green IT and IT governance. He has been involved in several regional, national, European and international research projects, including cooperation projects mainly with the Universities of Paraguay, Albania, Tunisia, Morocco and Ecuador. He has participated in more than 500 international conferences, workshops and congresses as a reviewer, session chair, and president of the program committee but mostly as a programme committee member or scientific committee member. He is co-author of more than 200 international papers (including journals, published reviews, proceedings and book chapters) and two university textbooks. Carlos Juiz is a senior member of the IEEE and also a senior member of the ACM. He is also an invited expert of the International Communication Union (ITU) and an Academic Advocate of ISACA. He has been also appointed as a member of the Domain Committee on Cloud Computing from IFIP until 2017. He was the Sub-director of the Polytechnic School (20042005) and Director of the Office of Planning and Prospective at the University of the Balearic Islands (2005-2007). He was the President's Delegate of New Technologies (2007-2011) and Vice-rector for Information Technologies (2011-2013) at UIB. Carlos Juiz was the Director of the Chair from Telefonica at UIB (2012-2014). Currently, he is one executive vice-president at the TURISTEC cluster and also a board member of the Balears.T cluster. He is the coordinator of the workgroup of Governance of IT AENOR, the Spanish body in ISO and has been coeditor of the ISO/IEC 38503 standard.