The Internet of Things (IoT) for Sustainability: A Framework for Costa Rica

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Abstract

The Internet of Things (IoT) has revolutionized our lifestyle and work patterns by connecting multiple internet-connected devices, applications, sensors, and machines, thereby generating substantial amounts of data through wired or wireless connections. This emerging technology has witnessed rapid growth in recent years and holds immense promise for promoting sustainability. Despite various initiatives implemented in Costa Rica to support sustainability and individual efforts to harness the potential of the IoT, there is still a lack of a comprehensive framework to assist businesses and the government in implementing and measuring outcomes. Globally, approximately 75% of IoT projects concentrate on five sustainable development goals (SDGs). This study aims to develop a conceptual framework that delineates a strategy for utilizing the IoT to foster sustainable development in Costa Rica. This framework adopts a holistic approach to sustainability, encompassing economic, social, and environmental considerations. Furthermore, it strives to integrate digital technologies into sustainability endeavors to optimize their impact. This study's findings suggest substantial potential for the technology to contribute to sustainable development in the country. However, several challenges must be addressed to fully capitalize on its benefits.

Keywords: Internet of Things; IoT; Sustainability; Sustainable Development Goals

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Introduction

The rationale of this research on the Internet of Things (IoT) as a case study lies in its potential to promote sustainability. IoT technology enables the interconnection and data exchange between various devices and systems, facilitating efficient resource management, reduced energy consumption, and improved environmental monitoring. By analyzing and optimizing data collected from IoT sensors, organizations can enhance operational efficiency, minimize waste, and make informed decisions toward sustainable practices. Moreover, IoT-driven applications can empower individuals and communities to monitor and control their energy usage, leading to more responsible consumption patterns. Thus, studying the relationship between IoT and sustainability can provide valuable insights into harnessing technological advancements for a more environmentally conscious future.

IoT refers to a network of multiple internet-connected devices, applications, sensors, and/or machines, which enable the generation of substantial volumes of data through wired or wireless connections (Furstenau et al., 2022a; Rejeb et al., 2022; Sánchez-Cano et al., 2021; Shorfuzzaman & Shamim Hossain, 2021). The proliferation of IoT has experienced significant growth in recent years, attributed to various factors such as the widespread adoption of advanced hardware and software platforms, increased availability of cloud-based servers and communication networks, and the evolution of big data analysis (Furstenau et al., 2022a; Rejeb et al., 2022). The primary objective of the IoT is to enable internet connectivity for devices, applications, sensors, or machines that can establish connections directly or via a fixed-infrastructure-based IoT.

An IoT platform comprises four fundamental components: a) collection, which encompasses the devices, applications, sensors, and/or machines responsible for gathering data, as well as the framework for transmitting this data; b) storage, which serves as the central repository for organizing and processing the data; c) processing, which involves employing computing paradigms to transform the raw data into processed data; and d) visualization, which involves presenting the data to stakeholders in a manner that facilitates their comprehension (Li et al., 2023). It is worth emphasizing that the energy consumption associated with digitization services is currently a significant concern, given its exponentially growing demand and the projected 56% increase by 2040 (Al-Obaidi et al., 2022).

Despite the rising demand for energy consumption resulting from digitalization services, there is a projected global growth of 147% in renewable energy consumption over the next three decades. Moreover, investments in clean energy have surged approximately tenfold from 2004 to 2019, and the proportion of renewable power in global energy generation has increased from 5.2% in 2007 to 13.4% in 2019, respectively (Li et al., 2023). Consequently, numerous studies have explored how the IoT can enhance the sustainability of countries. This is achieved through various applications that promote sustainable policies and by enabling more efficient energy consumption from devices, applications, sensors, and/or machines, as well as the underlying internet network. The IoT can enhance energy consumption by facilitating devices' improved efficiency in utilizing electricity from the power grid. Furthermore, it can create a "smart" environment by deploying intelligent algorithms that contribute to Smart Energy Management (SEM), thereby further optimizing energy usage.

One of the key opportunities presented by the advent of the digitalization era is the utilization of the IoT to enhance energy efficiency in built environments, thereby reducing energy demands and achieving

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sustainable development goals (Al-Obaidi et al., 2022). Sustainability, as defined by the United Nations, involves meeting the present needs while ensuring the ability of future generations to meet their own needs. Sustainable development goals serve as a framework for enhancing the well-being of global populations and mitigating the adverse impacts of climate change (Mukhi & Quental, 2019). Notably, the 11th development goal focuses on Sustainable Cities and Communities, aiming to foster inclusive, safe, resilient, and sustainable cities and human settlements (Ismagiloiva et al., 2019). In this context, technology carries the responsibility of improving sustainability through various means, and the IoT plays a vital role in fulfilling this purpose.

IoT devices serve various applications, such as the creation of "Smart Cities." This concept entails establishing a network that facilitates information exchange and communication within a city, utilizing the acquired data to enhance the residents' quality of life (Sánchez-Cano et al., 2021). Similarly, IoT finds application in "Smart Home" technologies, which involve devices, applications, sensors, or machines that provide digitally connected, automated, or enhanced services to household occupants through internet connectivity (Furszyfer Del Rio et al., 2021). These two applications of IoT are interconnected, as they aim to improve the well-being of citizens and household occupants within urban and residential settings, serving as examples of the aforementioned smart energy management approach.

Another instance of the IoT's application for sustainable purposes is the implementation of eco-routing. This technology aims to optimize traffic distribution in urban areas, thereby enhancing mobility sustainability. However, its real-life implementation presents challenges due to the need for diverse information and the integration of multiple sensors into existing city infrastructure. Despite these challenges, the value of such a service is significant, particularly in light of the pressing issue of air pollution and its detrimental effects on human health, as highlighted by Aguiar et al. (2022). The authors noted that, according to the European Environmental Agency, even with pollutant emission reductions resulting from pandemic restrictions, a substantial percentage (95% for fine particulate matter and 89% for Nitrogen Oxides) of the urban population in 2020 exceeded the World Health Organization (WHO) guidelines. These findings underscore the severe consequences of air pollution for human health (European Environment Agency, 2020).

From a holistic perspective, the IoT represents a burgeoning technology that harbours the immense potential for fostering sustainability. In the realm of sustainable development, Costa Rica stands as a celebrated exemplar, often hailed as the greenest nation worldwide. This commendation stems primarily from the country's resolute dedication to renewable energy sources (Okot et al., 2022). Notably, Costa Rica surpasses the 99% mark in terms of electricity generation from renewable sources, with hydroelectric power contributing to approximately 78% of the overall energy mix. Furthermore, Costa Rica exhibits a commendable commitment to conservation, as evidenced by the safeguarding of over 25% of its land area through national parks and reserves.

Costa Rica is relevant in terms of IoT and its relationship with sustainability due to its unique contextual and institutional elements. The country has a strong commitment to environmental conservation and has made remarkable progress in achieving renewable energy targets. Costa Rica's rich biodiversity and natural resources provide a compelling context for implementing IoT solutions that monitor and manage ecosystems, wildlife, and sustainable agriculture. The country's stable political and economic environment, coupled with its investment in education and technology infrastructure, creates a favourable institutional framework for IoT innovation and adoption. Costa Rica's emphasis on sustainability as indicated in the National Decarbonization Plan 2050 and its supportive ecosystem make it a compelling case study for understanding the potential of IoT in driving environmental conservation and sustainable development.

This case study contributes to the literature by highlighting the relationship between IoT and sustainability, offering insights into how IoT technology can be utilized to address environmental challenges. It emphasizes the potential of IoT to enable sustainable practices, resource optimization, and energy efficiency. By exploring the intersection of IoT and sustainability, researchers can expand the existing scope of literature on both topics, providing empirical evidence, theoretical frameworks, and practical implications for various stakeholders and guiding governance policy development. The case study can serve as a reference point for scholars studying sustainable technologies, IoT applications, and their impact on environmental sustainability. It also encourages further research and discussions on the role of IoT in promoting sustainable development and the potential challenges and ethical considerations associated with its implementation.

Methodology

The research applied a systematic literature review research as it ensures a comprehensive and inclusive analysis by systematically searching and reviewing a wide range of relevant studies. Secondly, this methodological approach allows for the synthesis of existing knowledge, enabling a holistic understanding of the research topic by integrating findings from multiple sources. Additionally, the methodology minimizes bias through predefined inclusion and exclusion criteria, enhancing the credibility and reliability of the investigation. Moreover, it facilitates the identification of research gaps, providing valuable insights for future research directions.

To conduct a literature review, a systematic research methodology was conducted, which includes the following steps:

Define the research question: The first step in conducting a literature review is to clearly define the research question or topic. This will help to narrow down the scope of the review and ensure that it remains focused on the key issues.

Search for relevant literature: The next step is to search for relevant literature. This can be done using a variety of databases, such as PubMed, Google Scholar, and Web of Science. The search terms used should be specific and relevant to the research question.

Screen the literature: Once the relevant literature has been identified, the next step is to screen it to determine which studies are most relevant to the research question. This can be done by reading abstracts, titles, and keywords.

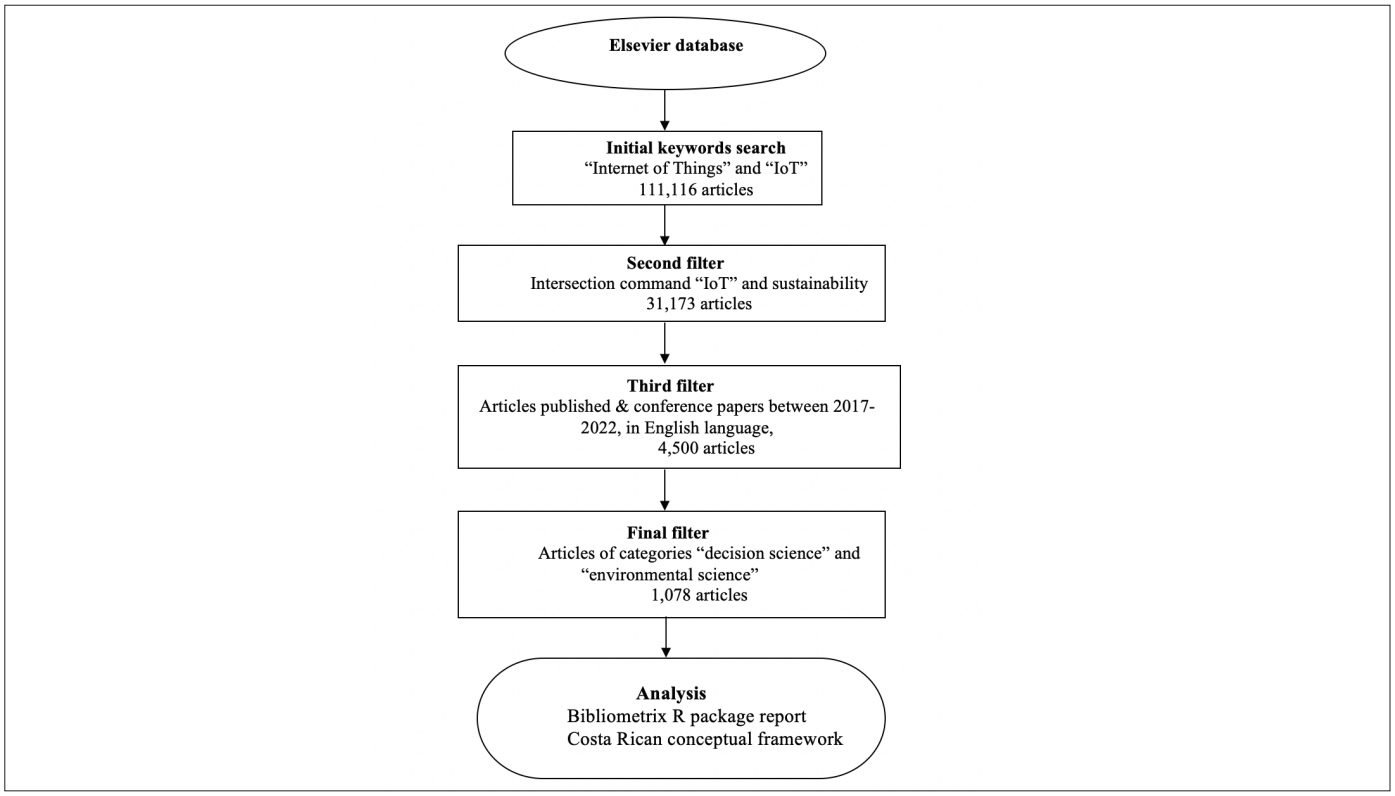
Read and analyze the literature: After screening the literature, the next step is to read and analyze it in detail. This involves critically evaluating the quality of the studies, identifying patterns, and highlighting areas of agreement and disagreement.

Synthesize the literature: The final step is to synthesize the literature by drawing conclusions and identifying key themes. This involves organizing the literature into meaningful categories and summarizing the key findings (Snyder, 2019).

Initially, the keywords "Internet of Things" and "IoT" were employed to conduct a preliminary search, yielding a total of 111,116 articles. Subsequently, to focus the search on the intersection of IoT and sustainability, the keyword "sustainability" was added, resulting in a refined set of 31,173 articles. To further narrow down the search results, various filters were applied based on specific categories, such as "more recent (less than 5 years)" and "research article." These refinements culminated in a subset of 4,500 articles for further examination. To enhance the relevance of the retrieved articles, additional filters were applied, including categories such as "decision sciences" and "environmental sciences," resulting in a reduced set of 1,078 articles that were eligible for review. Moreover, in addition to utilizing international sources, a localized approach was adopted by conducting 100 searches on university platforms and local databases to gather information from national sources, thereby ensuring a comprehensive range of perspectives for the research.

The research aimed to gather information from national and international sources to provide a better understanding of the topic of IoT and sustainability and its relationship. We opted for the Elsevier database as a filter for the documentation processes due to the following justifications: Elsevier is a renowned and reputable academic publisher, known for its rigorous peer-review process and high-quality publications. The database provides access to a wide range of scholarly journals and conference proceedings, ensuring comprehensive coverage of the latest research in the field. Moreover, Elsevier's indexing and search capabilities allow for efficient filtering and retrieval of relevant articles, facilitating the identification of key studies and advancements in the specific area of IoT and sustainability. Researchers can rely on the credibility and relevance of the articles obtained from the Elsevier database, enhancing the validity and robustness of their investigation. To filter and analyze data in terms of author relevancy, semantic network collaboration, and world collaboration map, we used a literature review bibliometric approach where we analyzed data from 2017-2022 as detailed in Figure 1. We installed the Bibliometrix application with a full data analysis package (version 4.1.3-06/15/2022) to conduct bibliometric analysis based on the parameters mentioned above (Aria & Cuccurullo 2017). Finally, with this analysis, we were able to contextualize the state of the art regarding IoT and sustainability and suggest a guiding framework for Costa Rica.

Figure 1. Article classification and selection framework.



Note: the data was run on 28 February 2022, Elsevier data repository.

The chosen articles played a pivotal role in exploring and addressing the following key research questions, forming the foundational basis for our conceptual framework:

What are the existing global sustainability initiatives utilizing IoT?

Which of these initiatives hold the potential for enhancing sustainability in Costa Rica?

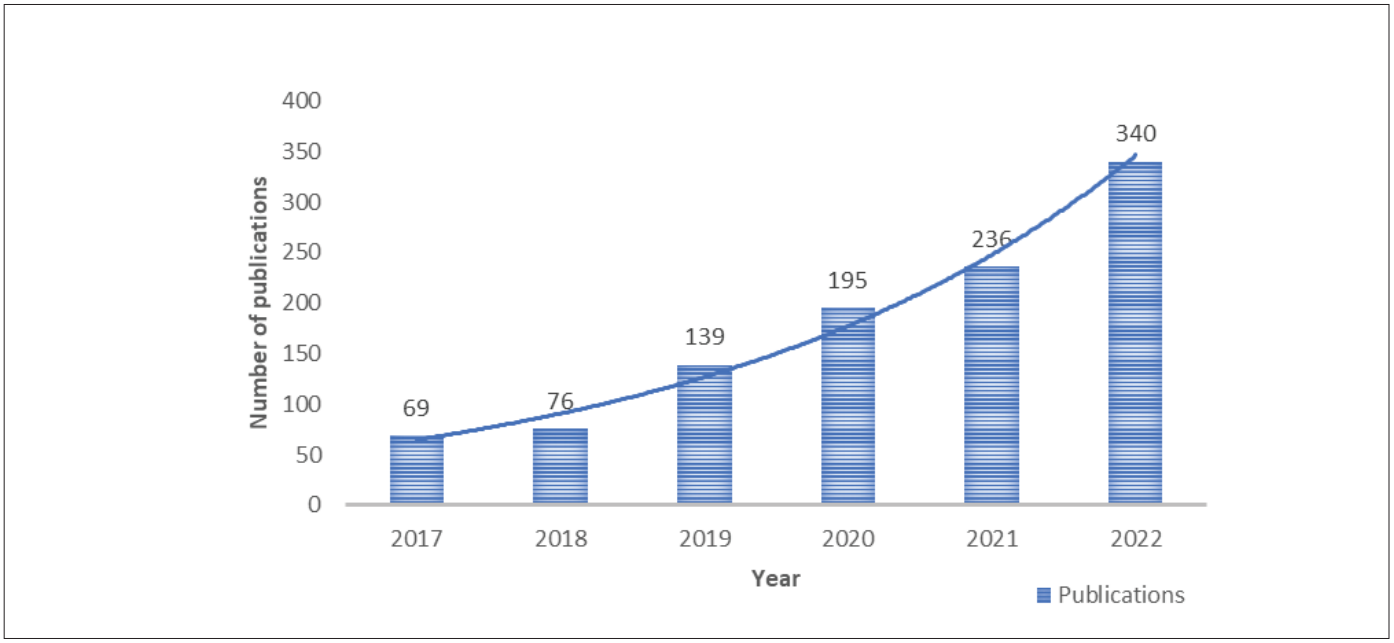
What are the potential advantages and benefits of leveraging IoT for sustainability in Costa Rica?

These questions guided our investigation and analysis, allowing us to develop a comprehensive framework that aims to harness the potential of IoT for sustainable development in Costa Rica.

Results and discussion

The current research undertook a comprehensive literature review, identifying and retrieving a total of 1,087 scientific articles that aligned with the selected descriptors for the search, covering the period from 2017 to 2022. As depicted in Figure 2, the analysis reveals a remarkable exponential growth in the number of publications investigating the relationship between IoT and sustainability. In 2017, a mere 69 articles met the search criteria, while in 2022, with the year still ongoing, the count of published articles has already reached 340. This significant surge in research output over the past five years underscores the escalating scholarly interest and attention dedicated to this field of study.

Figure 2. Number of publications over time (2017-2022).

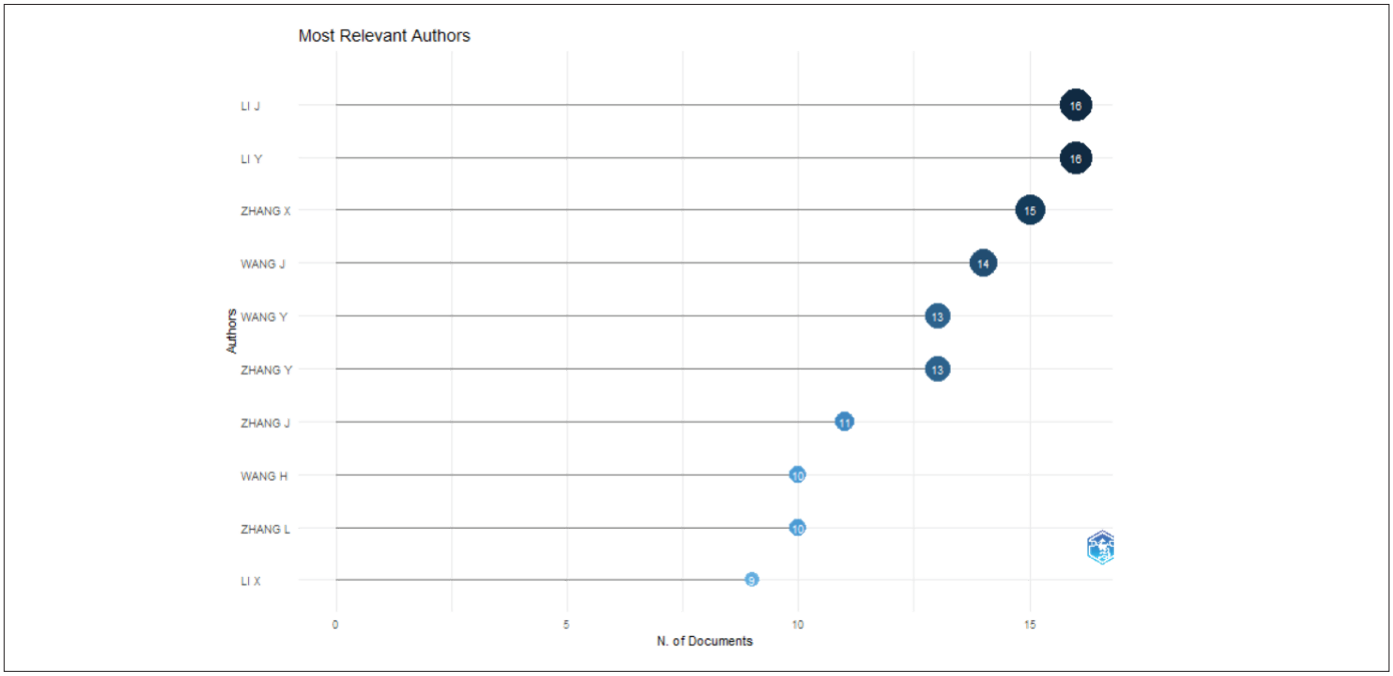


Note: Source: Own elaboration

The escalating volume of published research focusing on the integration of IoT, and sustainability underscores the pivotal role of IoT in fostering a sustainable paradigm. To delve deeper into this domain, we conducted a systematic categorization of the prevalent themes associated with the keywords IoT and sustainability from 2017-2022, employing the specific categories of "decision sciences" and "environmental sciences". Our meticulous analysis revealed three overarching themes: humans, IoT-Smart cities, and IoT-Energy efficiency. These topics, along with their pertinent relationship to IoT, are elucidated and explored comprehensively in the subsequent sections.

Regarding the most relevant author in relation to the research topics, we can observe in Figure 3 that Li J and Li Y have the greatest number of documents published totalling to 16 documents. These publications are highlighted in dark blue, followed by Zhang X with a total of 15 documents published. It is also crucial to mention that these two authors have the most collaborations with other authors. Li X and Zhang L have the lowest number of documents published thus 9 and 10 respectively.

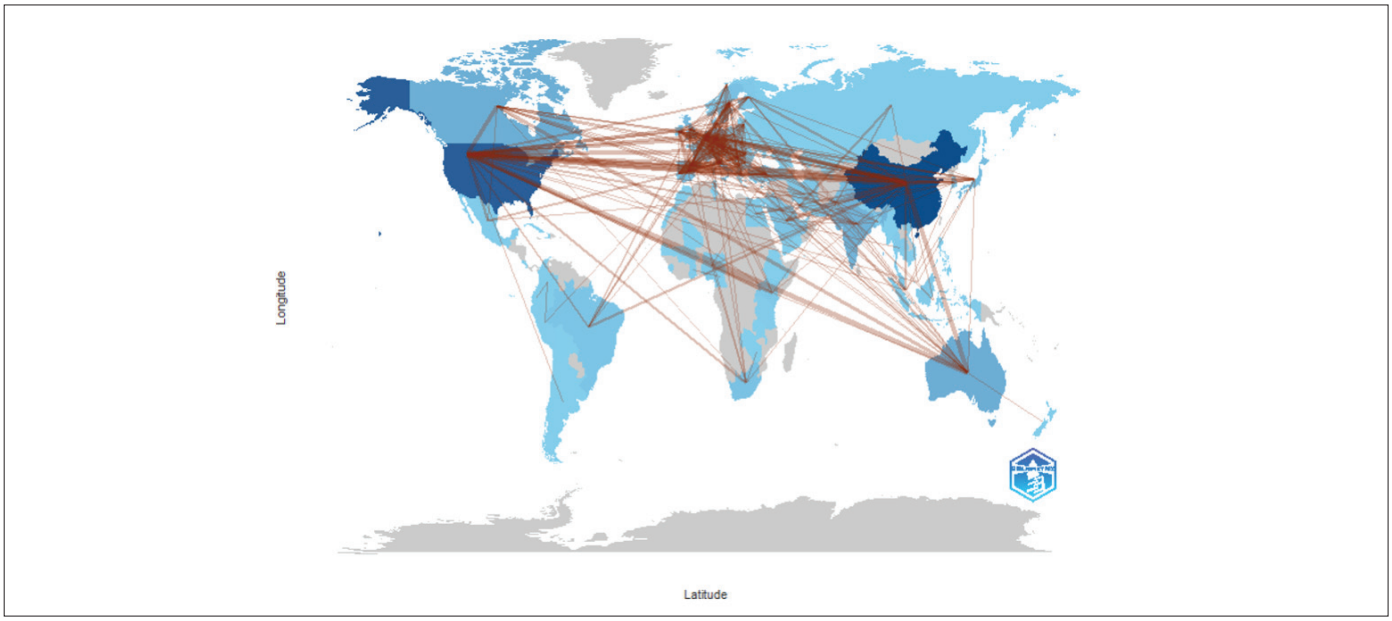
Figure 3. Most relevant authors.



Note: Adapted from Elsevier database. Bibliometrics R report.

Figure 4 below illustrates a collaboration world map among authors from different countries. It is evident that the collaboration between China and the USA has the highest frequency of 17, surpassing other countries. This indicates a strong interest from authors in these nations regarding the development of IoT and sustainability. The collaboration between the USA and China can be attributed to several factors. Both countries recognize the urgent need to address global challenges, and IoT plays a crucial role in accelerating most of these solutions. Moreover, the USA's expertise in innovation, Research, and Development, combined with China's robust manufacturing potential, foster a synergistic partnership. Furthermore, shared interests in sustainable development and resource management incentivize joint efforts to develop cutting-edge technologies that benefit both nations and the world. This also implies the existence of a wide range of valuable research from around the globe that can guide the establishment of IoT for sustainability in Costa Rica.

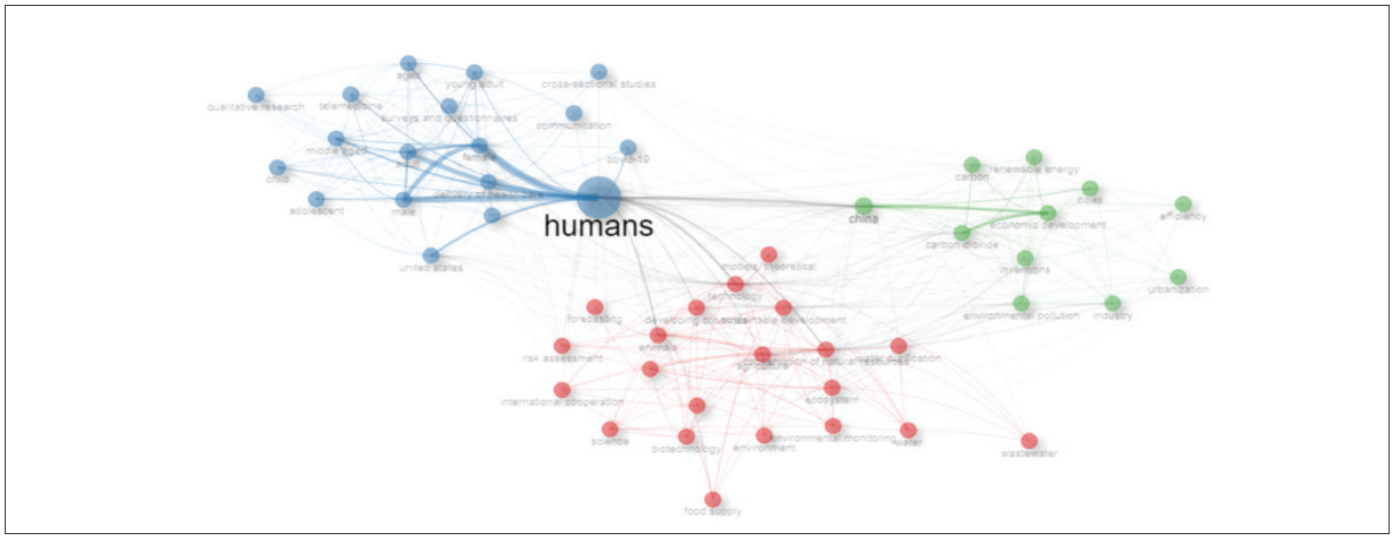
Figure 4. Collaboration world map.



Note: Adapted from Elsevier database. Bibliometrics R report.

The semantic network demonstrates thematic areas and their interconnections to IoT and sustainability. At the center of this pool are humans, further proving their crucial role in relation to IoT and sustainability. This also implies a directly proportional relationship between sustainability development and humans, as their activities can either promote or hinder progress in IoT and sustainability mechanisms. Therefore, for a successful Costa Rican framework, all actions and policy development must prioritize humans at the center of design and implementation.

Figure 5. semantic network collaboration.



Note: Adapted from Elsevier database. Bibliometrics R report.

A recent article in a journal pre-proof conducted a comprehensive analysis of potential research opportunities related to IoT, utilizing Bibliometric Performances and Network Analysis (BPNA) along with a Systematic Literature Review (SLR). The analysis identified a total of thirty-one distinct clusters, among which "IoT-Smart City" and "IoT-Energy" emerged as the 5th and 6th most prominent clusters, respectively. These clusters encompassed 115 and 77 core documents, with citation counts of 1,005 and 827, respectively. The top four clusters centered around IoT's associations with authentication, cloud computing, industry 4.0, and 6LoWPAN applications (Furstenau et al., 2022b). Recognizing the significance of the IoT-Smart City and IoT-Energy clusters and their potential contribution to the sustainability agenda, our research explores the intricate relationship between IoT-Smart City and IoT-Energy in greater detail.

IoT and Smart Cities

According to (Furstenau et al., 2022b):

> *"The Smart-City concept is mainly new and emerged in 2012 and can be seen as using the IoT and other emerging technologies to improve the functions of cities. IoT can be applied in heterogeneous environments and is the best way to improve smart cities."*

The fundamental objective underlying the concept of a Smart City is to harness the advanced information and communication capabilities of the telecommunications infrastructure to facilitate efficient resource management (Sánchez-Cano et al., 2021). While the integration of IoT is a key component, Smart Cities also encompass other vital features such as cloud computing. This integration of technologies allows Smart Cities to adopt a holistic approach that encompasses various facets, including smart homes and communities, urban sustainability, urban development, resource management, and more (Rejeb et al., 2022). The development of Smart Cities has garnered considerable attention due to the myriad of social, financial, and environmental benefits they offer (Alowaidi, 2022). In achieving the vision of a Smart City, smart homes play a pivotal role by enabling effective energy utilization, with IoT assuming a critical function in facilitating this transformation.

IoT has found applications across various domains, including homes and cities, with the aim of fostering sustainable development. A recent example includes the proposal of a fuzzy framework for smart home monitoring systems dedicated to wind and solar power in Saudi Arabia. This framework strives to establish an inference system equipped with histograms, which illustrate the correlations between an objective function, accurate information as control parameters, and electricity costs. By optimizing the utilization of home appliances, this framework contributes to mitigating air pollution and addressing climate change concerns arising from energy losses due to inefficient usage (Alowaidi, 2022).

In recent years, the prominence of solar power technology has grown significantly, owing to its widespread availability and adoption. It has become increasingly common to encounter a wide array of electrical devices that are either equipped with or compatible with solar panels.

Examples include security cameras, security lights, and solar water tanks, among others, which are rapidly gaining popularity in the market. Solar power offers numerous environmental and sustainability advantages, as it is not subject to regional limitations, can be deployed on-site, and is scalable. In China, an integrated system leveraging IoT was developed, facilitating the collaborative design of solar energy devices and buildings. This system aims to streamline the distribution and integration of solar energy devices with photovoltaic power generation technology (Wu et al., 2022).

Transportation represents another domain where the IoT finds application within smart cities. Fossil fuel usage plays a significant role in carbon dioxide emissions, which contribute to climate change, posing a substantial threat to sustainable development. In the United States, several studies have investigated the potential of IoT to enhance the efficiency of the railway system. These studies explore opportunities for advanced monitoring and maintenance practices, improved safety measures, enhanced service levels, and sustainable development. The research underscores the necessity for innovative hardware, artificial intelligence algorithms, and more efficient technologies that can enhance the overall performance of one of the country's most energy-intensive activities (Singh et al., 2022).

IoT and Energy Efficiency

While 5G technology has the potential to increase energy consumption and contribute to climate change, it also presents opportunities for IoT applications in the energy sector that can promote energy efficiency and sustainability. For instance, the deployment of IoT devices for monitoring and controlling energy consumption in buildings and homes can yield significant energy savings. Furthermore, the implementation of smart grids, which leverage IoT devices to optimize energy production and distribution, can contribute to enhanced energy efficiency and reduced carbon emissions. A study conducted in India exemplified the efficacy of a smart grid system, which resulted in a 35% reduction in energy consumption and a 30% increase in the utilization of renewable energy sources (Saravanan et al., 2022). These findings underscore the potential benefits of IoT-enabled solutions in mitigating energy-related challenges and fostering sustainable practices.

As mentioned by (Sánchez-Cano et al., 2021):

> *"They highlight that the main challenges of a Smart City go through the management of energy power based on models that consider energy efficiency, as it is a key tool for the development of household production processes, companies, and industries. Although they only occupy 2% of the earth's surface, they consume 75% of the world's energy and generate 80% of greenhouse gasses."*

Indeed, smart cities have a pivotal role to play in effectively managing energy consumption stemming from IoT devices by implementing efficient energy management systems. Through such measures, smart cities can actively contribute to building a more sustainable future by mitigating energy waste and optimizing resource utilization. Furthermore, IoT has the potential to foster sustainable practices by influencing energy consumer behaviour and enhancing energy efficiency in domains like home automation (Aboltins & Blumberga, 2018). This transformative shift towards a sustainable and energy-efficient future holds paramount importance in addressing the challenges posed by climate change and realizing global sustainable development goals.

Current sustainability initiatives in Costa Rica

Costa Rica, a small nation in Central America, has achieved remarkable strides in its pursuit of sustainable development initiatives. Valuing its biodiversity and natural resources, Costa Rica has emerged as an ideal setting for the advancement of sustainable practices. Notably, one of the nation's most notable achievements lies in its commitment to carbon neutrality. In 2021, Costa Rica secured a remarkable global ranking of third in the Environmental Performance Index (EPI) and became the world's first country to pledge complete carbon neutrality by the year 2050. This ambitious target has been bolstered by a series of comprehensive policies, including the implementation of carbon taxes and the establishment of renewable energy sources, such as hydro, wind, and geothermal energy (Cheng et al., 2023).

Costa Rica has made significant efforts to safeguard its forests through robust reforestation programs, resulting in a notable increase in forest cover from 21% in the 1980s to surpass 50% at present. Moreover, the nation has allocated more than 25% of its land area as protected areas, encompassing national parks and reserves, which have played a vital role in preserving its diverse biodiversity.

Another noteworthy endeavour in Costa Rica centers around sustainable tourism. The tourism industry constitutes a crucial economic contributor for the country, and Costa Rica has taken proactive measures to ensure its sustainability without compromising its natural resources. This includes the development of eco-tourism activities, such as bird watching and nature hikes, as well as the promotion of sustainable practices among hotels and other tourism-related businesses. These initiatives aim to strike a balance between economic growth and the preservation of Costa Rica's natural heritage.

In addition, Costa Rica has implemented policies to promote sustainable agriculture and reduce the use of harmful pesticides and fertilizers. The country also aims to eliminate single-use plastics by 2021, making it one of the first countries in the world to do so. Overall, Costa Rica's commitment to sustainability has led to significant progress in protecting its natural resources and reducing its carbon footprint. While there is still work to be done, the country's initiatives serve as a model for other countries looking to pursue sustainable development. On September 9, 2016, Costa Rica made a significant stride in its commitment to sustainable development by signing the National Pact for the Advancement of the Sustainable Development Goals. This historic event marked Costa Rica as the first nation to embrace the pact with the support of the United Nations, signifying the highest level of dedication toward the pursuit of sustainable development. As highlighted on the United Nations webpage, the National Pact aims to

enhance the quality of life and well-being of the Costa Rican population by fostering collaborative endeavors among the signatory stakeholders and mobilizing resources to achieve the outlined objectives (Jolly, 2007). This landmark commitment underscores Costa Rica's unwavering commitment to sustainable development and serves as a model for other nations.

The Technical Secretariat of the Sustainable Development Goals (SDGs) operates in a closely coordinated manner with the United Nations System in Costa Rica, striving to strengthen the execution of the 2030 Agenda. This collaborative effort focuses on enhancing the capacity of the sectors and actors who have signed the National Plan. The objective is to facilitate efficient planning and the development of policies, programs, projects, and other activities that align with the goals and principles of the 2030 Agenda. Furthermore, accountability processes are actively promoted to monitor progress and identify any gaps in the implementation of the SDGs. Through this collaborative framework, Costa Rica aims to foster effective and comprehensive advancement toward achieving the SDGs.

Among the 17 Sustainable Development Goals (SDGs), approximately 75% of IoT projects concentrate on five specific goals. Notably, two SDGs are particularly pertinent to the potential of IoT in advancing the objectives of the 2030 Agenda. These are SDG 7, which centers around affordable and clean energy, and SDG 11, which pertains to sustainable cities and communities. Additionally, three other SDGs that exhibit a close association with IoT include SDG 3, which aims to ensure good health and well-being, SDG 9, which focuses on industry, innovation, and infrastructure, and SDG 12, which strives for responsible consumption and production. The subsequent section will delve into a comprehensive examination of the goals associated with the two SDGs that demonstrate a more direct correlation with IoT (Henning & Yamileth, 2019).

#7. Affordable and clean energy

Guarantee universal access to affordable, dependable, and modern energy services.

Significantly increase the proportion of renewable energy in the set of energy sources.

Double the global rate of improvement in energy efficiency.

Increase international cooperation to facilitate access to clean energy research and technology, including renewable sources, energy efficiency, and advanced and cleaner fossil fuel technologies, and promote investment in energy infrastructure and clean technologies.

Expand infrastructure and improve technology to provide modern and sustainable energy services for all in developing countries, especially least developed countries, small island developing States, and landlocked developing countries, in line with their respective support programs.

#11. Sustainable Cities and Communities

Provide access to safe, accessible, and sustainable transport systems for all and improve road safety, through the expansion of public transport, paying special attention to the needs of people in vulnerable situations, women, children, people with disabilities, and the elderly.

Increase inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable planning and management of human settlements in all countries.

Reduce the negative per capita environmental impact of cities, including paying particular attention to air quality and the management of municipal and other waste.

Substantially increase the number of cities and human settlements that adopt and implement integrated policies and plans to promote inclusiveness, resource efficiency, climate change mitigation and adaptation, and disaster resilience, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015 -2030, comprehensive disaster risk management at all levels.

According to the United Nations representation in Costa Rica, the utilization of available funding from contributing partners for SDGs 7 and 11 has been relatively modest. Only 0.8% of the total funding allocated for SDG 7 (affordable and clean energy) and 14.5% of the funding earmarked for SDG 11 (sustainable cities and communities) has been utilized thus far. These funds have been channelled through diverse partners such as Municipalities, the Nacional Highway Council (CONAVI), and the Environment and Energy Ministry (MINAE), among others. The progress made in these initiatives is assessed and tracked through the SDG Index and Dashboards, as indicated in the Sustainable Development Report of 2022. Despite the formidable challenges posed by the COVID-19 pandemic, Costa Rica has displayed an upward trajectory in advancing these SDGs, reflecting commendable progress (Sachs et al., 2022).

According to the Sustainable Development Report of 2022, Costa Rica garnered a score of 73.5 out of 100 and achieved a performance index of 79.8 for its concerted efforts to enhance the well-being of its citizens. This positioning places Costa Rica at the 50th spot globally and the 4th position within Latin America, following Cuba (49th), Uruguay (41st), and Chile (30th). The country received a commendation for its accomplishments in meeting the sustainable development goal (SDG) of affordable and clean energy. However, further attention is required to address the SDGs pertaining to zero hunger, reduced inequalities, underwater life, life on earth, and peace, justice, and strong institutions (Camarillo, 2020). However, Costa Rica has developed numerous initiatives toward achieving the SDGs, with a focus on the following goals, in order:

Good health and well-being (SDG 3)
Sustainable cities and communities (SDG 11)
Industry, innovation, and infrastructure (SDG 9)
Responsible consumption and production (SDG 12)
Affordable and clean energy (SDG 7)

These initiatives are specifically designed to enhance the quality of life and overall well-being of the Costa Rican population. They are underpinned by collaborative efforts involving a multitude of stakeholders, as well as the mobilization of available resources to effectively accomplish the set objectives. To facilitate the planning, development of policies, programs, projects, and other endeavours that align with the goals and principles of the 2030 Agenda, the Technical Secretariat of the Sustainable Development Goals and the United Nations System work in close coordination. This collaborative framework aims to strengthen the implementation mechanisms of the 2030 Agenda in Costa Rica and build capacities within the sectors and actors that have committed to the National Plan (Jolly, 2007; Henning & Yamileth, 2019).

It is crucial to acknowledge that while Costa Rica has prioritized the aforementioned SDGs, this does not automatically imply that the country is substantially leading in these domains. There remains a substantial amount of work to be done to fortify different sectors, and Costa Rica is actively taking measures to bridge these disparities. The subsequent strategic areas outline Costa Rica's efforts toward attaining sustainable development that endures over time:

Climate change mitigation and adaptation
Biodiversity conservation and sustainable use of natural resources
Promotion of economic development that is environmentally sustainable and socially inclusive.
Promotion of social inclusion, with an emphasis on reducing inequality and poverty
Promotion of human rights and gender equality
Promotion of quality education and training for all
Promotion of innovation and technology transfer for sustainable development

These areas of focus reflect Costa Rica's commitment to achieving the SDGs and creating a sustainable future for its citizens. Costa Rica has already made significant progress in many of these areas, but there is still much work to be done to ensure that the country continues to move toward a more sustainable and equitable future (Camarillo, 2020).

IoT and Sustainability in Costa Rica

IoT holds the potential to foster sustainable development in Costa Rica, a nation that has set ambitious targets to curtail its carbon footprint and achieve carbon neutrality by 2050. IoT can be harnessed across multiple sectors, encompassing energy, water management, agriculture, waste management, and transportation, to enhance resource utilization, diminish waste, and mitigate greenhouse gas emissions.

IoT-enabled smart grids have the capacity to optimize energy consumption in Costa Rica, thereby minimizing wastage and bolstering efficiency. Intelligent water management systems can promptly detect and rectify leaks, conserving water-an invaluable resource within the country. The implementation of precision agriculture, facilitated by IoT, can amplify yields while concurrently reducing the use of harmful chemicals and curtailing waste generation. Additionally, IoT can track waste collection and disposal processes, enabling authorities to monitor real-time waste levels and optimize collection routes to diminish emissions emanating from garbage trucks. Furthermore, smart transportation systems can optimize traffic flow, thereby alleviating congestion and curtailing emissions arising from vehicles.
Nonetheless, the implementation of IoT systems in Costa Rica necessitates substantial investments in infrastructure, training, and research. Moreover, it is imperative to ensure that the design and implementation of IoT systems take into account data privacy and security concerns to prevent adverse repercussions on individuals and society. Further research is indispensable to assess the efficacy, costs, and social as well as environmental impacts of IoT-enabled sustainable development practices in Costa Rica and other nations.

According to the Costa Rica Investment Promotion Agency (CINDE), IoT is undergoing rapid expansion in the country due to several contributing factors. Notably, the declining costs of computing have rendered IoT technology more accessible for businesses to invest in. Furthermore, the prevalence of smartphones and the surge of cloud computing have simplified the collection and analysis of data from IoT devices, thereby fostering the growth of this industry in Costa Rica (CINDE, n.d.).

As per CINDE's report, IoT presents myriad opportunities for organizations to enhance their operational efficiency, ranging from streamlining supply chains to automating manufacturing processes. IoT technology can also assist businesses in cost reduction, augmenting customer service, and elevating the overall customer experience. Additionally, the IoT harbours substantial potential for equipment and product manufacturers to introduce innovative digital services and products. For instance, companies can leverage IoT technology to devise intelligent devices capable of data collection and real-time insights into customer behaviour, thereby enabling the provision of personalized services and products.

The burgeoning IoT industry in Costa Rica carries profound implications for the nation's economy and sustainability objectives. By embracing IoT technology, Costa Rican enterprises can optimize resource utilization, minimize waste, and curtail greenhouse gas emissions, thereby aiding the country in its pursuit of carbon neutrality by 2050. Moreover, the expansion of the IoT industry can engender fresh employment prospects in domains such as software development, data analytics, and engineering, thereby contributing to the nation's economic growth.

In conclusion, the expansion of the IoT industry in Costa Rica is propelled by various factors such as the declining costs of computing, widespread smartphone usage, pervasive connectivity, and the prevalence of cloud computing. This technology presents a multitude of opportunities for businesses to enhance operational efficiency, lower expenses, and introduce novel digital services and products. The growth of the IoT industry can also make notable contributions to the country's sustainability and economic objectives by generating fresh employment prospects and positioning Costa Rica as a frontrunner in the advancement of innovative IoT solutions.

Costa Rica has emerged as a prominent center for the advancement and deployment of cutting-edge IoT solutions. Several prominent enterprises, including Establishment Labs, Hewlett Packard Enterprise, Intel, Wunderman Thompson, and Qorvo, have established their presence in the country, capitalizing on its advantageous geographic location, skilled workforce, and favorable business environment to foster IoT innovation (Giuliani, 2008).

One exemplary company operating in Costa Rica is Establishment Labs, which has developed an integrated chip capable of capturing, tracking, and extracting intricate patient and product characteristics within their aesthetic breast implants. Collaborating with Intel Mega Lab, the company has introduced a novel scanner for personalized devices, harnessing the potential of IoT technology to enhance patient outcomes and streamline processes.

Hewlett Packard Enterprise (HPE) in Costa Rica has a primary focus on devising solutions that harness data analysis to minimize expenses, enhance security, and optimize efficiency by implementing IoT technologies. HPE's emphasis on the Intelligent Edge has facilitated the creation of pioneering solutions that offer real-time insights and empower informed decision-making.

As a global frontrunner in IoT technology, Intel has established a Product Development Engineering Team in Costa Rica dedicated to the company's IoT Group. This presence enables the development of more intelligent and interconnected solutions suited for a rapidly evolving world. Intel's active involvement in Costa Rica has been instrumental in propelling IoT technology innovation, generating fresh prospects for businesses and contributing to the country's economic advancement.

Wunderman Thompson, a hybrid agency, consultancy, and technology company, has fully embraced 4.0 tools, including IoT, to create groundbreaking solutions for its clients. The Costa Rican Hub of the company has effectively harnessed IoT technology to bring devices to life, simplifying everyday tasks and enhancing client satisfaction. Additionally, Qorvo, a renowned provider of RF solutions for mobile phones, infrastructure, and aerospace industry applications, has established a state-of-the-art facility in Costa Rica to expedite the adoption of IoT products through connectivity solutions. Qorvo's presence in Costa Rica has been instrumental in driving IoT technology innovation, enabling businesses to develop interconnected and intelligent solutions for a rapidly evolving world.

In conclusion, Costa Rica has emerged as a central hub for the development and implementation of pioneering IoT solutions, primarily due to the presence of leading companies such as Establishment Labs, Hewlett Packard Enterprise, Intel, Wunderman Thompson, and Qorvo. These enterprises have effectively capitalized on the country's advantageous geographic location, skilled workforce, and supportive business environment to foster IoT technology innovation, thereby making significant contributions to Costa Rica's economic growth and sustainability objectives.

The Foreign Trade Promoter of Costa Rica (PROCOMER) reports that the current global market value of IoT stands at US$ 190 billion and is anticipated to exhibit a Compound Annual Growth Rate (CAGR) of 29% until 2025. As stated by PROCOMER (2020), 46% of companies operating within Costa Rica's Industry 4.0 ecosystem specialize in providing IoT solutions. Furthermore, a study conducted by Deloitte and the Centre for Telecommunications Studies in Latin America highlights Costa Rica as the second most prepared country in the region for the implementation of IoT solutions. Given these advantageous circumstances, Costa Rica possesses a promising opportunity to foster initiatives that leverage IoT applications to bolster sustainability across various sectors.

Potential Applications for Sustainability

The utilization of IoT devices holds substantial potential in enhancing sustainability endeavors across diverse sectors. Concerning water conservation, IoT devices can effectively monitor water consumption in residential and commercial settings, promptly notifying users when levels are low or when water is being squandered. In the context of renewable energy sources such as solar, wind, and hydroelectric power, IoT devices offer the capacity to track and monitor their usage, enabling users to optimize their energy consumption. Additionally, IoT devices can play a vital role in waste management by monitoring waste levels and identifying strategies to curtail waste generation while promoting recycling. In the realm of air quality, IoT devices can swiftly detect hazardous levels of pollutants and promptly alert users. Lastly, in the domain of sustainable agriculture, IoT devices prove invaluable in monitoring crop growth, soil fertility, water utilization, and pest control. Leveraging the data gleaned from these devices, farmers and agricultural entities can make informed decisions pertaining to their operations, thereby bolstering sustainability initiatives within the sector.

Costa Rica Sustainability Framework with IoT

The Costa Rica Sustainability Framework with IoT is a comprehensive framework designed to harness the capabilities of IoT in order to accomplish sustainability objectives within the country. This framework adopts an integrated approach to leveraging IoT devices' potential, with the ultimate aim of enhancing energy efficiency, mitigating greenhouse gas emissions, and fostering the preservation of natural resources. The primary objective of this framework is to provide decision-making support at both the industry and national levels, thereby facilitating the adoption of IoT technologies to advance sustainability initiatives. By implementing this framework, Costa Rica can effectively capitalize on the advantages offered by IoT devices, ensuring that the country's sustainability goals are efficiently and effectively achieved.

The framework focuses on four key areas.

The Costa Rica Sustainability Framework with IoT endeavours to capitalize on IoT technologies to propel sustainability initiatives in

various pivotal domains. Within the energy sector, the framework aims to curtail energy consumption and enhance energy efficiency by developing intelligent energy devices and systems, such as smart meters and grids, while integrating renewable energy sources into the energy landscape. Concerning waste management, the framework strives to augment waste management practices through the creation of systems and devices capable of monitoring, collecting, and analyzing waste data to diminish waste generation.

In the realm of environmental protection, the framework aims to enhance practices by establishing systems and devices proficient in monitoring, collecting, and analyzing environmental data, with the aim of reducing the impact of human activities on the environment. Lastly, the framework aspires to foster conservation practices by fostering systems and devices that can monitor, collect, and analyze data pertaining to biodiversity, ecosystems, and natural resources. By promoting conservation practices and safeguarding natural resources, the framework aims to engender sustainability across diverse sectors in Costa Rica. Through these initiatives, the framework effectively harnesses the potential of IoT technologies to attain its overarching sustainability objectives.

Implementation Strategy

In order to harness the potential of IoT technologies and propel sustainability initiatives in Costa Rica, it is imperative to establish a comprehensive regulatory framework that ensures the safety, security, and environmental sustainability of all IoT devices employed in the country. This framework should encompass guidelines pertaining to data privacy and security, along with regulations governing the utilization of IoT devices and services. Furthermore, the framework should incorporate incentives, such as tax breaks, subsidies, and other incentives, to encourage businesses and individuals to embrace IoT technologies.

To safeguard personal data and adhere to data protection laws, the regulatory framework should include provisions for data privacy and security. This necessitates the encryption and secure storage of all collected IoT data, as well as the implementation of robust security measures by IoT service providers to protect customer data.

Alongside the regulatory framework, the development of an IoT platform is crucial to facilitate seamless communication and data sharing among different IoT devices in Costa Rica. This platform would enable the monitoring and tracking of energy usage, water consumption, waste management, and other sustainability metrics. To initiate data capture, sensors would need to be deployed across the country in key locations such as residences, businesses, and public areas. Educational resources and events should also be designed to educate citizens and businesses on the effective utilization of the platform.

Lastly, the implementation of data collection from diverse IoT devices is essential to monitor and analyze sustainability metrics. For instance, data could be gathered from smart meters to monitor energy usage, water sensors to track water conservation efforts, and waste management sensors to monitor waste generation and recycling practices. Through these concerted efforts, Costa Rica can effectively harness the power of IoT technologies to realize its sustainability objectives.

Harness the Power of Big Data Analytics: The Costa Rica Sustainability Framework should effectively leverage big data analytics to identify and address potential sustainability issues. Through the analysis of data collected from IoT devices, it becomes feasible to identify areas that require improvement and take proactive measures to tackle sustainability challenges.

Utilize AI and Machine Learning: In addition, the framework should make use of AI and machine learning techniques to enhance the automation and efficiency of sustainability endeavors. Machine learning algorithms can aid in predicting energy consumption patterns, optimizing resource utilization, and refining waste management practices.

Manage and Monitor Connected Devices: It is paramount to implement a robust system to manage and monitor connected devices, ensuring the security of data and optimized performance. The framework should encompass guidelines for device management, including processes for device registration, monitoring, and decommissioning.

Create an Open Platform: To foster innovation and encourage collaboration, the framework should establish an open platform that empowers developers and researchers to create applications that further enhance sustainability. This platform should provide access to data collected from IoT devices, along with tools and resources to facilitate the development of novel applications.

Establish Partnerships: To ensure effective implementation and monitoring of sustainability efforts, forging partnerships with both public and private organizations is crucial. By collaborating with various stakeholders, it becomes possible to leverage their expertise and resources to develop more impactful sustainability initiatives.

Challenges and Opportunities

The integration of IoT technology in Costa Rica presents a formidable tool for realizing sustainability objectives. The Costa Rica Sustainability Framework with IoT offers a holistic approach that harnesses the potential of IoT to enhance energy efficiency, waste management, environmental protection, and conservation. Nonetheless, the implementation of IoT faces various challenges, including the necessity for reliable infrastructure, appropriate skills and training, adequate funding, and privacy and security concerns. To tackle these challenges, further research is indispensable to delve into the legal, ethical, and regulatory aspects associated with IoT, as well as to determine the most effective methods for leveraging the newfound data and its impact on sustainable development goals. By successfully addressing these challenges and capitalizing on the opportunities presented, Costa Rica has the potential to emerge as a regional leader by effectively implementing IoT to accomplish its sustainability goals.

Implications for Costa Rica

The establishment and execution of an IoT and sustainability framework in Costa Rica hold considerable consequences for multiple stakeholders and present promising advantages for the nation's environmental and socio-economic situation.

Through the utilization of IoT technology, Costa Rica can bolster its environmental conservation endeavors. The application of IoT sensors for real-time data collection and monitoring empowers the efficient management of natural resources, the protection of wildlife, and the preservation of ecosystems. The IoT framework enables early detection of environmental threats, aids in optimizing energy consumption, and supports effective waste management systems, all in line with the country's dedication to sustainability and biodiversity preservation.

The integration of IoT into agriculture practices has the potential to transform the sector in Costa Rica. By implementing IoT-based solutions for irrigation management, pest control, and crop monitoring, the agricultural industry can benefit from precise, data-driven insights. This optimized resource utilization and increased crop yields not only promote sustainable agricultural practices but also play a significant role in enhancing food security and ensuring economic stability.

Costa Rica's urban regions have the potential to become smart and sustainable cities through the integration of IoT technologies. By employing IoT sensors for monitoring and managing energy consumption, traffic flow, waste management, and air quality, cities can make informed decisions based on evidence. The adoption of smart grids and intelligent transportation systems can further enhance energy efficiency and reduce carbon emissions, ultimately leading to an improved quality of life for residents.

The implementation of an IoT and sustainability framework has the potential to spur economic growth and encourage innovation in Costa Rica. Embracing IoT technologies can attract investments, foster entrepreneurship, and open avenues for local businesses to develop and implement IoT solutions. This, in turn, may lead to job opportunities, technological progress, and the establishment of a thriving IoT ecosystem, positioning Costa Rica as a prominent regional leader in sustainable technology.

The implementation of an IoT and sustainability framework calls for the creation of enabling policies and regulatory structures. This presents Costa Rica with a chance to develop strong guidelines and standards that govern the ethical and responsible utilization of IoT technologies. It also entails fostering collaboration among the government, academia, industry, and civil society to ensure effective governance, privacy protection, and data security.

Finally, by leveraging IoT technology and embracing sustainability principles, Costa Rica has the capacity to progress in environmental conservation, sustainable agriculture, smart city initiatives, economic development, and policy and governance. This approach will pave the way for a more sustainable, resilient, and prosperous future for the country.

Conclusion

Numerous ongoing sustainability initiatives worldwide are utilizing IoT technology to great effect. One prominent example is the "Smart Cities" concept, which aims to integrate various technologies, including IoT, to enhance citizens' quality of life while minimizing the environmental impact of urbanization. In Amsterdam, for instance, smart street lighting has been implemented to reduce energy consumption, while in Barcelona, smart parking solutions are being developed to alleviate traffic congestion and reduce air pollution. Moreover, IoT sensors are being deployed in agriculture to optimize resource utilization and enhance crop yields.

Many of these initiatives can be adapted and implemented in Costa Rica to enhance sustainability within the country. For instance, the establishment of smart grids and the integration of renewable energy sources into the energy mix can significantly reduce the country's reliance on fossil fuels. The application of IoT technology in waste management can improve the efficiency of waste collection and disposal processes, as well as mitigate waste generation. Furthermore, the utilization of IoT sensors in agriculture can optimize resource usage and foster increased crop yields, thereby promoting sustainable agricultural practices.

The potential advantages of leveraging IoT for sustainability in Costa Rica are multifaceted. Firstly, the integration of IoT technology has the potential to facilitate the achievement of the country's sustainability objectives by enhancing energy efficiency, curtailing greenhouse gas emissions, and fostering the conservation of natural resources. Secondly, IoT technology can furnish decision-makers with real-time data concerning energy consumption, waste management, and other sustainability metrics, empowering them to make well-informed choices regarding resource allocation and utilization. Finally, the utilization of IoT technology holds the promise of stimulating economic growth by engendering new industries and job opportunities associated with the development and implementation of IoT solutions tailored for sustainability initiatives.

Nevertheless, unlocking the complete potential of an IoT and sustainability framework in Costa Rica necessitates robust policy backing, cooperation among diverse stakeholders, and a dedication to safeguarding privacy and data security. By enacting stringent guidelines and regulations, the nation can guarantee the responsible and ethical application of IoT technologies while fostering an environment that supports innovation and entrepreneurship.

In general, the implementation of an IoT and sustainability framework in Costa Rica represents a proactive stance in working towards a greener, more resilient, and prosperous future. This underlines the country's dedication to sustainable development, positioning Costa Rica as a prominent regional leader in utilizing technology for

environmental conservation and socio-economic advancement. By engaging in meticulous planning and execution, Costa Rica can harness the transformative power of IoT to build a sustainable and inclusive society for generations to come.

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