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Research Paper
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Knowledge Mapping And Bibliometric Analysis Of ESP32-Based Iot Heat Index Monitoring For Smart Classrooms: Research Trends, Collaboration Networks, And Future Research Directions (2010–2025)

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Abstract

Classrooms in tropical, resource-constrained settings are increasingly exposed to heat stress, and the ESP32 microcontroller has emerged as a low-cost platform for building the Internet of Things (IoT) sensing nodes needed to monitor it. However, the scholarly literature that would situate ESP32-based heat index monitoring for smart classrooms within the broader IoT research landscape remains fragmented. This study presents an expanded, large-scale bibliometric and science-mapping analysis of 17,831 IoT-related journal articles indexed on Lens.org between 2010 and 2025, processed with the bibliometrix/Biblioshiny R package and VOSviewer following a four-stage retrieval, preprocessing, analysis, and interpretation workflow. The dataset shows a 48.14% annual growth rate and an average of 33.94 citations per document, with annual output rising from fewer than 20 documents in 2010 to a peak of 3,547 in 2022, before dipping in 2023–2024 and rebounding to 2,911 in 2025. Logistic growth modeling estimates a publication saturation ceiling of 21,732 cumulative documents, with the field's peak annual output already reached (2022.4) and 84.9% of variance explained. Sensors (Basel, Switzerland) dominates the source landscape with nearly 3,000 cumulative articles, while the Chinese Academy of Sciences leads institutional output (250 documents); at the individual-researcher level, output is led by Do-Hyeun Kim (37 documents), Rajesh Singh (27), and Zhong Lin Wang (26), and productive authorship clusters into nationally homogeneous co-authorship groups (Chinese, Korean) with minimal cross-cluster bridging. A country level choropleth of publication totals confirms this concentration at the macro scale, both the United States and China are the two major nodes of output with no publications from Southeast Asia indicated in light. Strategic thematic map identifies the themes "IoT, sensors, smart city" and "internet of things, energy efficiency, wireless sensor networks" as motor themes, while keyword co-occurrence map with its temporal overlay indicates a clear transition from network-infrastructure related keywords (2020–2021) to wearable, biosensing and well-being related keywords (2022–2023). Importantly, "heat index", "ESP32" and "smart classroom" never join the keyword network as high-frequency, independent keywords pointing to this application type as a nascent subspecialty within a rapidly evolving parent field. The study concludes with five concrete future-research directions — standardized sensor design, predictive analytics, energy-autonomous deployment, expanded tropical/Southeast Asian participation, and open longitudinal datasets — to help close this gap.

Keywords: ESP32; Internet of Things; heat index monitoring; smart classroom; bibliometric analysis; bibliometrix; VOSviewer; thematic mapping; co-authorship network; author productivity; geographic

1. Introduction

Rising ambient temperatures and increasingly frequent heat events place classrooms — particularly in tropical countries such as the Philippines — among the indoor environments most exposed to heat-related discomfort and health risk for students and teachers alike. Because standard classroom cooling infrastructure is often absent or insufficient in public schools, low-cost, connected sensing devices have emerged as a practical means of tracking heat exposure and triggering timely interventions. The ESP32 microcontroller, with its integrated Wi-Fi/Bluetooth connectivity, low cost, and low power consumption, has become a preferred platform for building such Internet of Things (IoT) environmental-monitoring nodes, and is already used in a wide range of classroom temperature, humidity, and air-quality monitoring systems (Cañas & Hernández, 2024; Navarrete-Sanchez et al., 2025; Rahmadani et al., 2023; Widjaja et al., 2022).

At the same time, the volume of IoT-related scholarship has grown so rapidly — this study's own dataset spans 17,831 journal articles from 3,360 sources — that individual researchers can no longer track the field through manual literature review alone. Bibliometric analysis, supported by tools such as the bibliometrix R package and VOSviewer, offers a reproducible way to characterize the structure, growth, and thematic evolution of a research domain and to surface gaps that individual narrative reviews may overlook (Aria & Cuccurullo, 2017; Donthu et al., 2021; van Eck & Waltman, 2010). Bibliometric and scientometric studies of the broader IoT literature (Kumar et al., 2022; Leong et al., 2021; Tanko et al., 2023; Verma et al., 2025) and of specific IoT sub-domains such as healthcare (Asghar et al., 2023), home automation (Kim & Wang, 2023), and cybersecurity (Ganji & Afshan, 2024) have proliferated in recent years, yet no prior study has specifically mapped the intersection of ESP32-based sensing, heat index monitoring, and smart classroom applications at this scale, and fewer still have extended such mapping down to individual-author productivity and country-level geographic distribution.

This study addresses that gap by conducting a large-scale bibliometric and knowledge-mapping analysis of the IoT literature most relevant to ESP32-based heat index monitoring for smart classrooms, covering the period 2010–2025. Specifically, the study seeks to answer the following research questions: (1) What is the annual growth trend, citation-impact profile, and expected saturation point of the relevant literature? (2) Which authors, journals, and institutions lead output, and what does their distribution reveal about the field's structure? (3) What are the dominant thematic clusters and strategic-diagram position of the literature, and where does heat index/ESP32-specific research sit within that structure? (4) How have these themes evolved over time, and what does the co-authorship network reveal about collaboration patterns? (5) What does the global geographic distribution of research output reveal about regional representation, particularly for tropical and Southeast Asian contexts? and (6) What research gaps and future directions follow from these patterns, particularly for smart classroom applications in tropical contexts?

2. Materials and Methods

2.1 Data Source and Retrieval Strategy

Bibliometric data were retrieved through a four-stage dataflow (Figure 1). In the first stage, literature was retrieved from Lens.org, a free scholarly and patent database that provides transparent, exportable metadata on authorship, institutional affiliation, citation counts, and open-access status (Penfold, 2020). A query combining Internet of Things terms ("Internet of Things," "IoT," "ESP32," "microcontroller"), heat/thermal terms ("heat index," "thermal comfort," "environmental monitoring"), and educational/sensing-context terms was applied, with filters restricting results to the 2010–2025 window and to the journal-article document type; records were then exported with full metadata in CSV/RIS/BibTeX format for downstream processing.

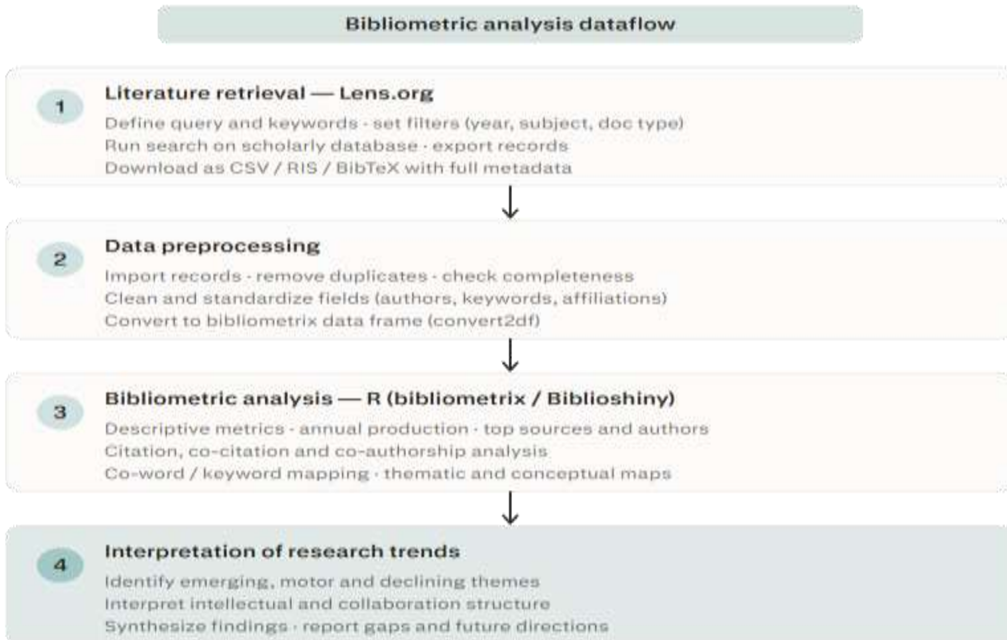

Figure 1. Four-stage bibliometric analysis dataflow: literature retrieval, data preprocessing, bibliometric analysis, and interpretation of research trends.

2.2 Data Preprocessing and Descriptive Overview

In the second stage, records were imported into R, duplicates were removed, and author, keyword, and affiliation fields were cleaned and standardized before conversion into a bibliometrix data frame (convert2df). The resulting corpus (Figure 2) comprises 17,831 documents — all journal articles — drawn from 3,360 sources over a 2010–2025 timespan, with a 48.14% annual growth rate, an average document age of 4.3 years, and an average of 33.94 citations per document. The dataset contains 668,730 references, 43,565 keywords-plus terms and an equal number of author keywords, and 61,921 distinct authors, of whom only 1,146 authored 1,260 single-authored documents; the mean number of co-authors per document is 5.53. The reported international co-authorship share of 0% is almost certainly an artifact of incomplete country-level affiliation tagging in the exported metadata rather than a genuine absence of cross-border collaboration, and should be treated as a data-quality limitation rather than a substantive finding (see Section 4.5).

Description	Results
Timespan	2010:2025
Sources (Journals, Books, etc)	3360
Documents	17831
Annual Growth Rate %	48.14
Document Average Age	4.3
Average citations per doc	33.94
References	668730
Keywords Plus (ID)	43565
Author's Keywords (DE)	43565
Authors	61921
Authors of single-authored docs	1146
Single-authored docs	1260
Co-Authors per Doc	5.53
International co-authorships %	0
journal article	17831

Figure 2. Descriptive statistics of the bibliometric dataset (2010–2025), bibliometrix/Biblioshiny.

2.3 Analytical Tools and Science Mapping

In the third stage, descriptive metrics (annual production, source, institution, and author rankings, citation and open-access profiles) were computed using the bibliometrix R package and its Biblioshiny web interface (Aria & Cuccurullo, 2017), which is widely used for reproducible science mapping (Kirby, 2023; Passas, 2024). Individual-author productivity was ranked by total document count, consistent with the descriptive approach to authorship concentration used in Lotka's-law-based bibliometric studies (Kushairi & Ahmi, 2021). Publication life-cycle modeling was performed by fitting a three-parameter logistic (S-curve) growth function to annual and cumulative publication counts, a standard approach in technology-diffusion forecasting (Jha & Saha, 2020). Keyword co-occurrence networks, thematic strategic diagrams, and co-authorship networks were constructed and visualized in VOSviewer (van Eck & Waltman, 2010), with cluster membership denoted by node color and network position determined by a force-directed layout. Country-level output was mapped as a choropleth to visualize the global geography of scientific production, following established approaches to geographic science mapping (Pan et al., 2012). The fourth stage — interpretation of research trends — is presented in Sections 3 and 4 below, following the same workflow depicted in Figure 1.

3. Results

3.1 Publication Growth Trend

Figure 3 shows the annual distribution of journal articles matching the search strategy. Prior to 2013 the volumes per year were insignificant (less than 50 per year) but increased regularly until the mid 2010s achieving approximate levels of around 780 items in 2018/2019 and around 1,200 items in 2019. This rapidly increased to approximately 1,930 items in 2020, then increased further to 3,010 items in 2021 before peaking at 3,547 items in 2022. Subsequently this declined to around 1,820 items in 2023 and around 1,770 items in 2024, but increased again in 2025 reaching close to 2,911 items; This fits well the overall rise to a peak with a partial recovery associated with multiple other IoT research subareas entering a maturation phase (Kumar et al., 2022; Leong et al., 2021).

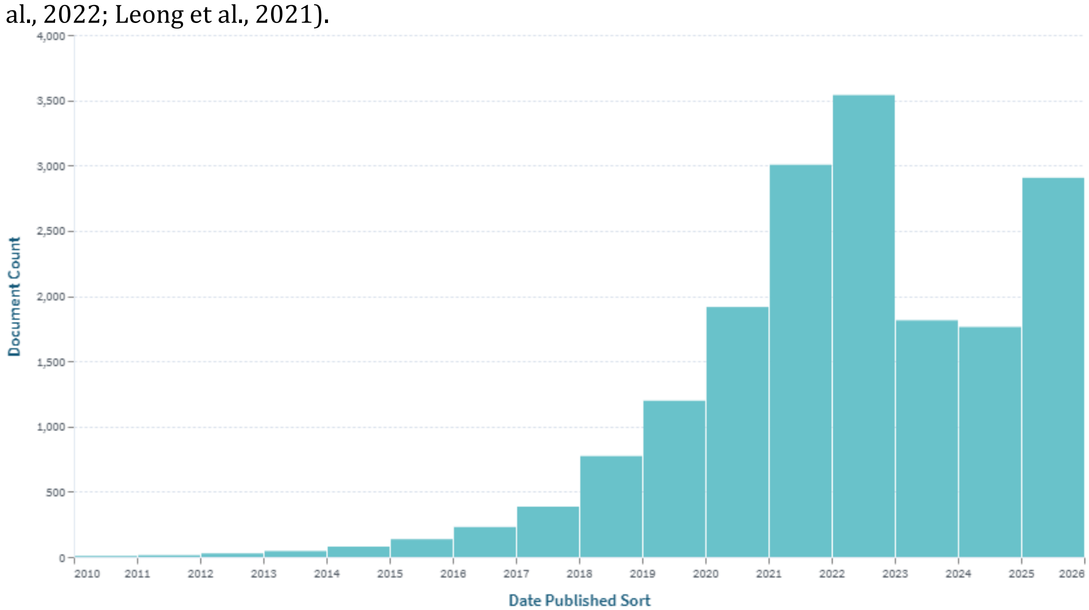

Figure 3. Annual distribution of journal articles matching the search strategy (2010–2025), Lens.org.

3.2 Citation Impact Over Time

Figure 4 shows the average citations per publication, over time, by date of publication. Citation impact rose from under 2 per paper in 2010, up to a range around 3-5 through the next four years, before rising steadily from 2017-2025, peaking in the 2020s with strong increases that peaked at 8.0 papers in 2020 and reached a high point of 8.2 papers in 2023 that began to drop through 2025. This recent downward trajectory can be attributed to citation lag, not declining quality, as papers published last year had insufficient time to accrue citations.

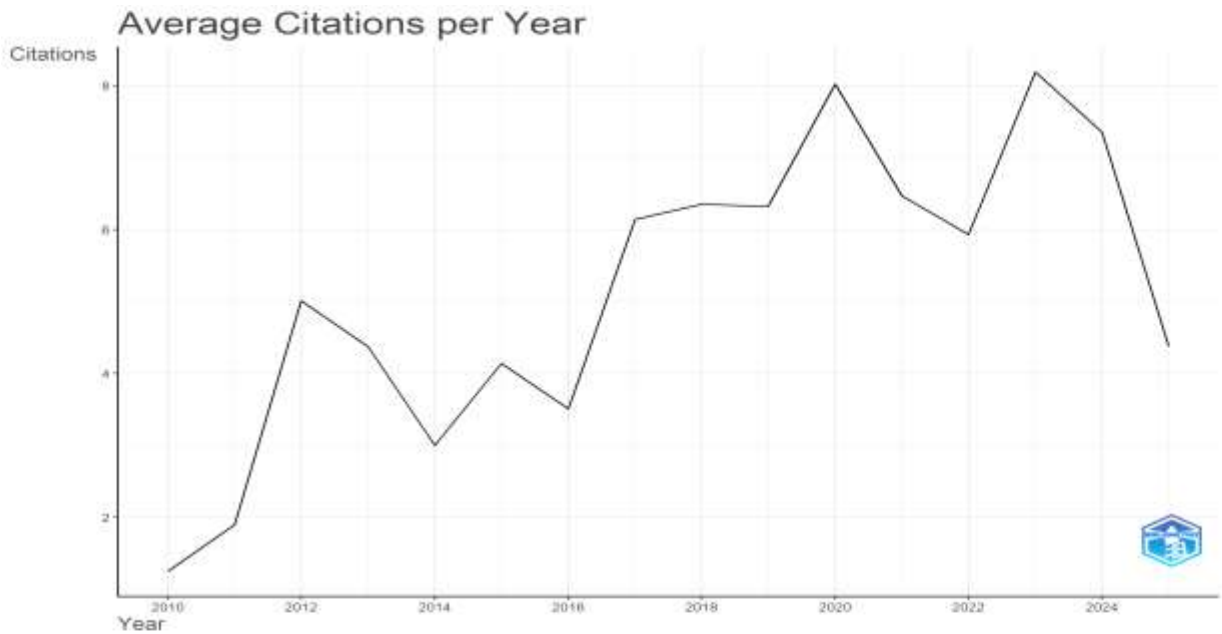

Figure 4. Average citations per year for journal articles in the dataset, bibliometrix/Biblioshiny.

3.3 Leading Journals and Their Growth

Figure 5 tracks the cumulative production of the five leading source journals over time, and Figure 6 ranks the top 20 source titles by total document count. Sensors (Basel, Switzerland) is by far the dominant outlet, accounting for nearly 3,000 cumulative articles by 2025 and exhibiting the steepest, still-accelerating growth curve of any source. Scientific Reports (~760 documents), Sustainability (~630), Energies (~520), and Applied Sciences (~450) form a distant second tier, each showing more moderate, recently plateauing growth. The remaining top-20 sources — including Electronics, Heliyon, Micromachines, PLoS One, and Biosensors — each contribute fewer than 250 documents, indicating that the field's publishing activity is heavily concentrated in a small number of open, multidisciplinary engineering and applied-science journals rather than being spread evenly across a broad journal base.

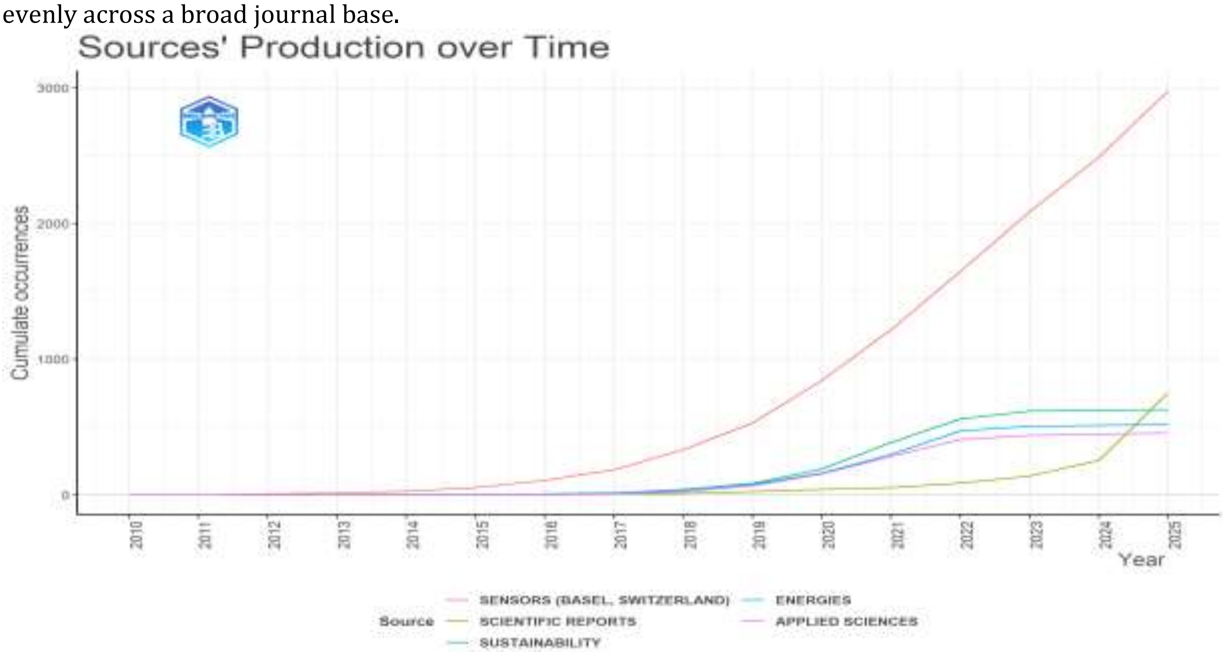

Figure 5. Cumulative production over time for the five leading source journals, bibliometrix/Biblioshiny.

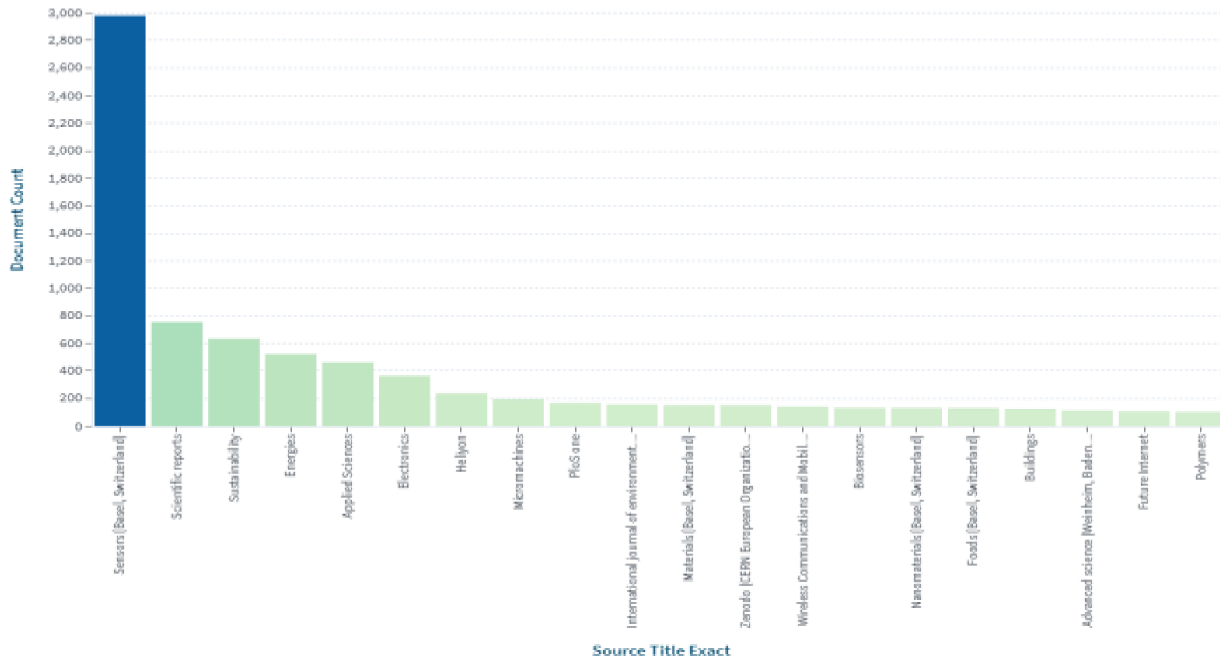

Figure 6. Top 20 source titles by document count, Lens.org.

3.4 Leading Institutions

Figure 7 shows institutional output for the ten leading contributors. Dominated by the Chinese Academy of Sciences, providing almost 250 papers - more than double the output of second placed Consiglio Nazionale delle Ricerche (120), and being trailed by King Saud University (110), National University of Singapore (100), University of Chinese Academy of Sciences (98), Zhejiang University (95), and Tsinghua University (90). The major contributions are seen to come predominantly from Eastern Asia, Middle East, and European institutions - there are no Southeast Asian or Philippine institutions appearing, despite the high exposure of these regions to classroom heat stress and increasing influence in low cost IoT prototypes. This absence highlights a geographic representation gap that recurs at the author level (Section 3.5) and the country level (Section 3.12), and is directly relevant to the future-research agenda proposed in Section 4.6.

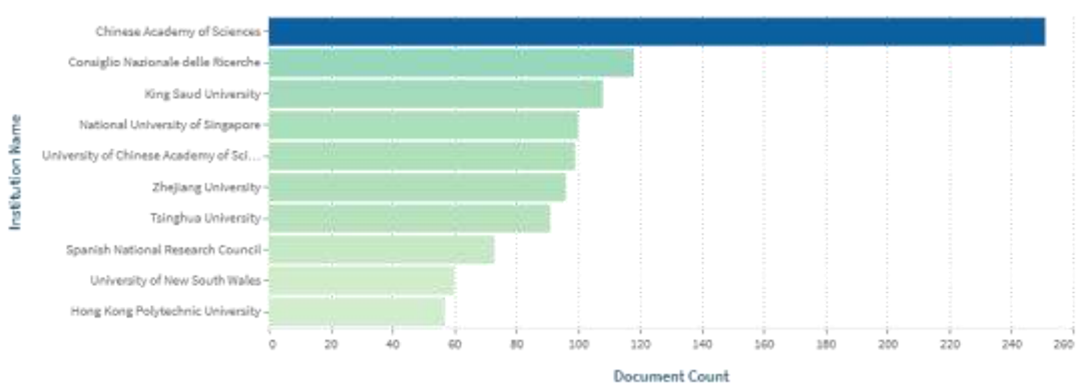

Figure 7. Ten leading institutions by document count, Lens.org.

3.5 Leading Authors

Figure 8 ranks the twenty most prolific individual authors in the dataset by total document count. A distinct top tier, highlighted in the chart, is led by Do-Hyeun Kim (37 documents), followed by Rajesh Singh (27), Zhong Lin Wang (26), Chengkuo Lee (25), and Anita Gehlot (23); these five authors alone account for a disproportionate share of the field's most active individual contributors, consistent with the concentrated productivity pattern typically described by Lotka's law of scientific authorship (Kushairi & Ahmi, 2021). A broader second tier contributes the remainder of the top-20 list: Jaime Lloret and Paolo Visconti (16 documents each), Joel J. P. C. Rodrigues (14), Ning Wang (13), Abdallah Elshawadfy Elwakeel, Hao Wang, and Yang Liu (11 each), and a cluster of authors with 9–10 documents apiece — Imran Ashraf, Imran Sarwar Bajwa, Wei Zhang, Antonio F. Skarmeta, Juan M. Corchado, Jun Wang, Lei Zhang, and Masayuki Takashiri. Notably, four of the twenty leading authors share the surname Wang (Zhong Lin Wang, Ning Wang, Hao Wang, Jun Wang), a pattern that visually corroborates the nationally clustered, surname-dense collaboration structure identified in the co-authorship network (Section 3.11). None of the twenty leading authors is affiliated with a Philippine or Southeast Asian institution, reinforcing — at the individual-researcher level — the same geographic concentration already visible in the institutional ranking (Section 3.4) and the country-level distribution presented later (Section 3.12).

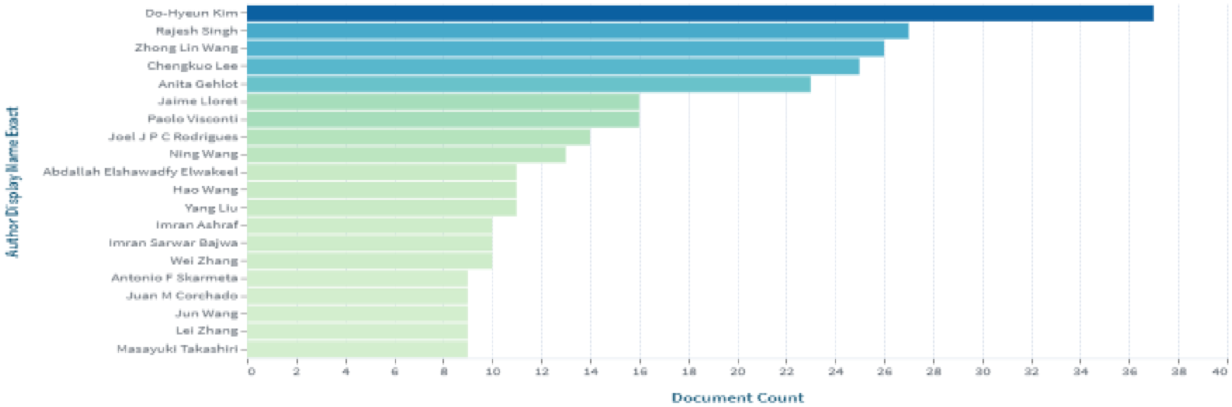

Figure 8. Twenty most prolific individual authors by document count, Lens.org.

3.6 Citation Network and Open-Access Distribution

Figure 9 combines a citing-scholarly-works bubble chart (top panel) with an annual scholarly-works bar chart (bottom panel). The largest citation bubbles — exceeding 1,600–1,800 citing works — cluster around articles published between 2019 and 2021, indicating that a small number of highly influential papers from that period continue to shape the field's citation structure. The bottom panel mirrors the growth pattern in Figure 3, with the number of underlying scholarly works peaking around 2020–2021 (over 200 per year) before declining. The color coding shows that the overwhelming majority of works are open access (blue), with only a small non-open-access minority (pale green), suggesting that the field is highly accessible to researchers in low-resource settings — a favorable condition for expanding classroom-level IoT research in the Philippines and other developing countries.

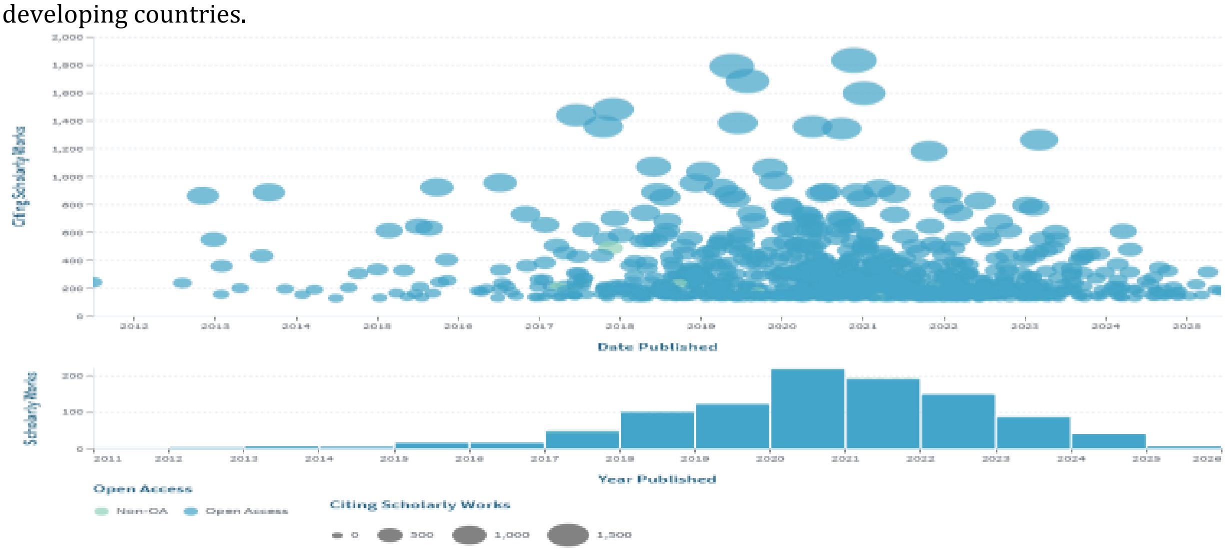

Figure 9. Citing scholarly works by publication date (top) and annual scholarly-works volume by open-access status (bottom), Lens.org.

3.7 Publication Life Cycle and Growth Forecast

Figure 10 presents a logistic (S-curve) life-cycle model fitted to the annual and cumulative publication data. The annual-publications fit (left panel) accounts for 84.9% of the overall variation (R = 0.849) and places 2022.4 as the peak year, fitting a peak production of 2,884 publications-a level quite close to the observed peak of 3,547 from Figure 3 and following this, the output has the potential to decline toward essentially zero new publications around 2045 if no significant external factor triggers new momentum. Similarly, the predicted cumulated curve (right panel) estimates the saturation level K 21,732 total papers, suggests the current research has approximately developed 82% of its cumulative potential papers, thus it has entered the last phase (deceleration) of the product life cycle (Jha & Saha, 2020). This prediction is a proxy for the life-cycle development of the general parent IoT/sensing literatures, not specifically heat index publication related to ESP32, that as indicated in Section 3.8 has not experienced yet thematic stability.

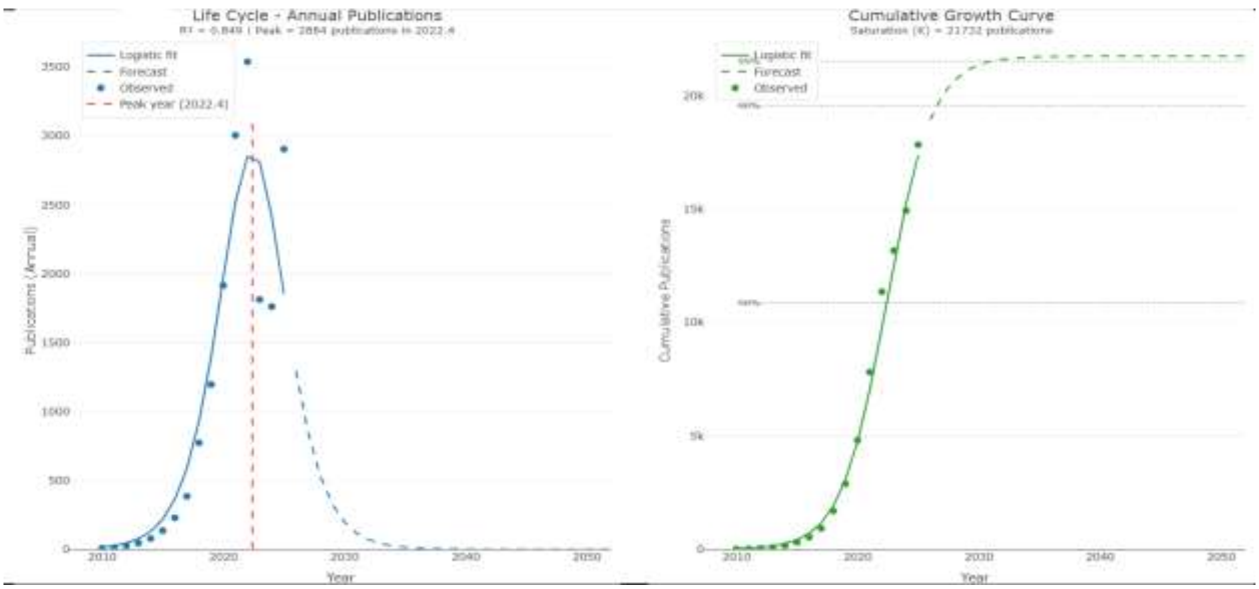

Figure 10. Logistic life-cycle model of annual publications (left) and cumulative growth curve with saturation estimate (right), bibliometrix/Biblioshiny.

3.8 Strategic Thematic Map

Figure 11 displays keyword clusters on a strategically positioned strategic centrality-density graph, positioning "IoT, sensors, smart city", and "internet of things, energy efficiency, wireless sensor networks" in the " motor-themes" segment (high centrality, high density) , a "favorable" and therefore mature research topic of particular importance as for driving the domain. "Machine learning, artificial intelligence, deep learning " is in the proximity of the "basic themes" limit because it reflects "well established but not so internally structured/organized " themes whereas "Internet of things (IoT), COVID-19, energy harvesting " and "blockchain, industry 4.0, sustainability" are in the " emerging or declining" position (low centrality, low density);"electrical and electronic engineering " is a n" isolated but concentrated" theme . No cluster corresponding to heat index monitoring or smart classrooms appears on the diagram at all, reinforcing the finding that this specific application has not yet generated enough concentrated literature to register as its own theme (Scarano et al., 2023).

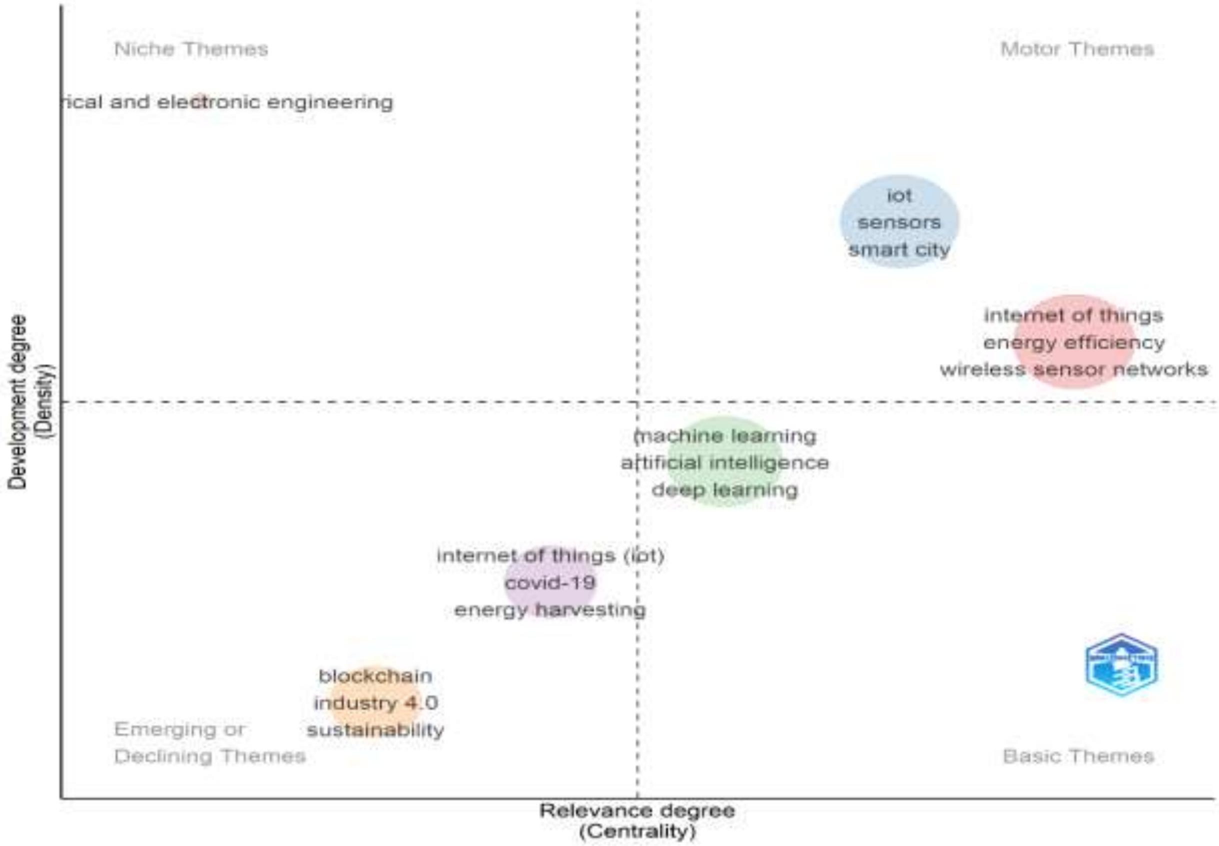

Figure 11. Strategic (centrality–density) thematic map of keyword clusters, bibliometrix/Biblioshiny.

3.9 Keyword Co-occurrence Network

Figure 12 presents the VOSviewer keyword co-occurrence network, in which node size reflects keyword frequency and color denotes cluster membership. Several broad clusters emerge: a green IoT-infrastructure cluster (internet of things, WSN, LoRa, routing, fog computing, computer security, home automation, ambient intelligence); a red sustainability/governance cluster (sustainability, big data, blockchain, bibliometric analysis, digitalization, construction 4.0, risk management); a cyan computing/pandemic cluster (machine learning, robotics, COVID-19, SARS-CoV-2); an orange/brown environmental cluster (environmental monitoring, air pollution, ecosystem, agriculture, hydrology); a blue biosensing cluster (biosensing techniques, graphene, nanotechnology, point-of-care, biomarkers analysis); and a yellow-green energy/well-being cluster (energy harvesting, wearable electronic devices, wearable devices, healthcare, aging, aged, gait, assistive technology). "Internet of things," "machine learning," and "wearable electronic devices" are the largest nodes overall, while terms directly tied to this study's focus — heat index, ESP32, and smart classroom — do not appear as independent, high-frequency nodes; instead, related concepts are dispersed across the IoT-infrastructure, environmental-monitoring, and energy/well-being clusters. This dispersion is itself an important finding: it indicates that ESP32-based heat index monitoring for classrooms has not yet consolidated into a recognizable thematic cluster within the broader literature, confirming its status as an emerging rather than an established research niche.

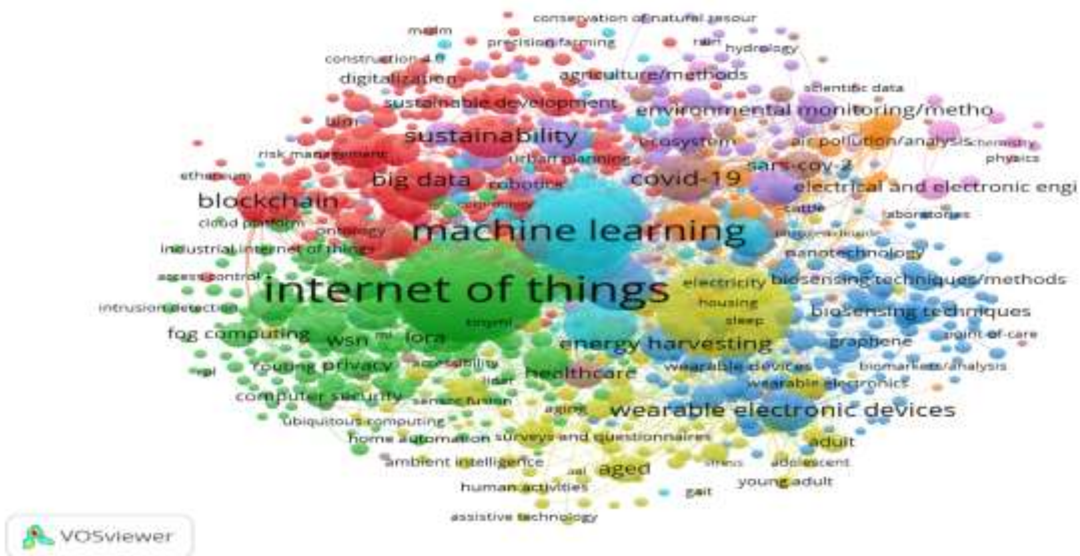

Figure 12. VOSviewer keyword co-occurrence network, clustered by color (cluster density view).

3.10 Temporal Evolution of Research Themes

Figure 13 displays the same keyword network with a color gradation on the average date of publication (dark purple/blue = 2020, yellow = 2023). Foundational terms about connectivity and governance-WSN, LoRa, routing, blockchain, sustainability, and digitalization-reside on the earlier (2020-2021) part of the gradient, evidencing an earlier formation of research on network infrastructure and sustainability. Wearable- and well-being-focused terms-wearable electronic devices, biosensor, gait, aged, adolescent, young adult-are positioned more towards the later half (2022-2023), indicating a evident thematic transition of the field from a connectivity and governance focus in IoT to a human health and well-being sensing perspective. The classroom heat index monitoring, as a very human-centric application focused on well-being and comfort, can be categorized in this recent trends with great potential growth for the near future, despite the lack of a specific group of very highly cited publications.

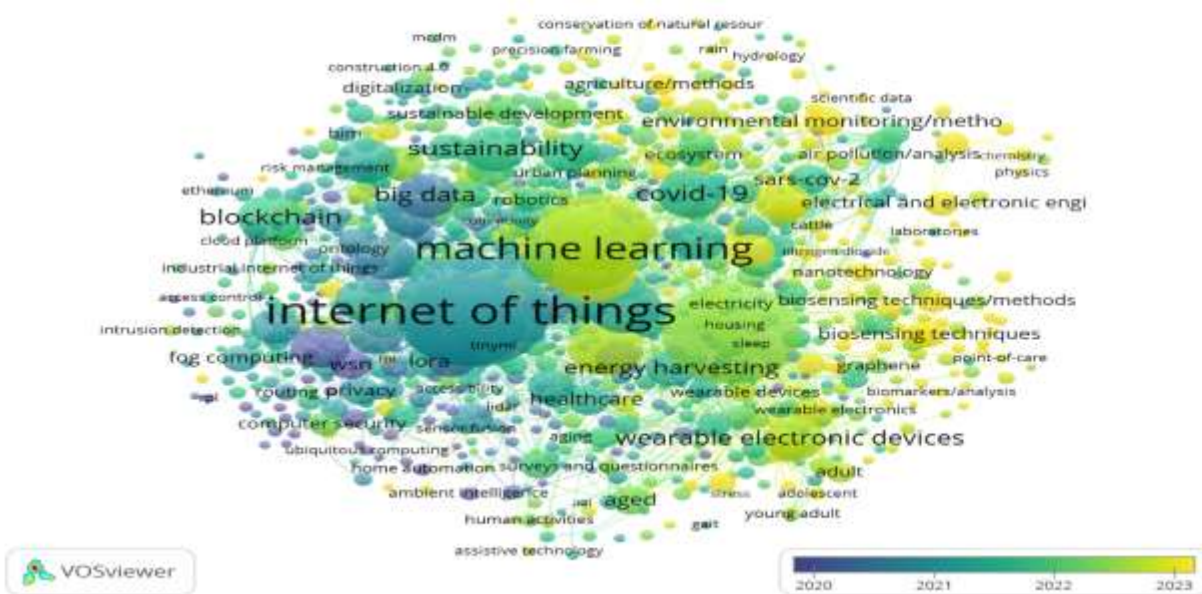

Figure 13. VOSviewer overlay visualization of keyword co-occurrence colored by average publication year (2020–2023).

3.11 Collaboration (Co-authorship) Network

Figure 14 displays co-author ships among highest degree individuals in the network. The network is separated into a variety of tightly clustered but nearly independent clusters that seem to be broadly along national lines; a red dominated cluster that has Wang Y, Zhang Y, Li Y, and Liu Y (authors having predominantly Chinese looking name patterns); a blue led cluster containing Wang Z and Zhang H; a small green cluster that has Liu X and Wang Q clustered around it; a separate purple cluster which has the authors Kim S, Lee S, Kim J, and a collaboration cluster of authors with surnames S and/or A in their name (Kim, Lee, Kim, and Kumar,for instance)-although, even here, the authors in the last named cluster seem somewhat apart from the rest of this section of the network and form their own clustering hub with minimal ties back into the red group. There is even an isolated pair of nodes (e.g. Voulodimos D and Katsadis D) that isn't connected at all to the main four-and-one(with small group clusters) component structure showing there can indeed be researchers that appear not to interact at all with major collaboration hubs in the field. This overall pattern seems strongly consistent with (a) the (likely artifact) 0%international authorship noted in Section 2.2 which would intuitively seem related to this pattern of international collaboration groups but not to international research itself, and(b) the surnaming of individual clustering revealed among highest degree lead authors, mentioned above in Section 3.5.

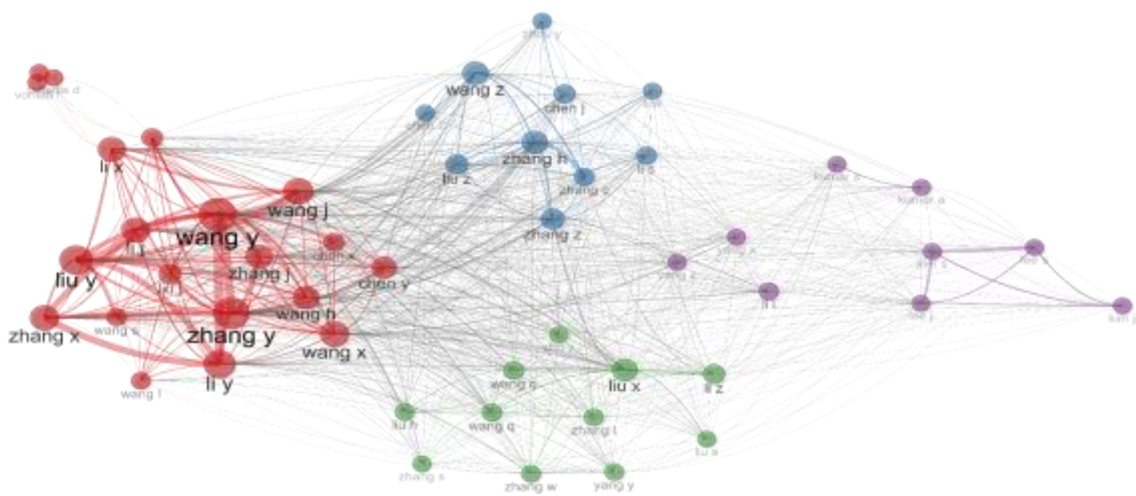

Figure 14. Co-authorship network among the most connected authors, colored by cluster, VOSviewer.

3.12 Geographic Distribution of Research Output

Figure 15 presents a world choropleth map of the geographic distribution of research output, with darker shading indicating a higher volume of documents attributed to a country's affiliated authors. China and the United States display the darkest shading and are clearly the two dominant contributors to the literature, consistent with their leading roles in institutional output (Section 3.4) and with the well-documented tendency for scientific output and impact to concentrate geographically (Pan et al., 2012). A second tier of moderately shaded countries — including India, Brazil, Australia, South Africa, and several Western European nations — contributes visibly but at a markedly lower volume. Most of Southeast Asia, including the Philippines, together with large parts of Africa and Central Asia, appears in the lightest shading band, indicating minimal recorded research output from these regions. This map provides direct, country-level corroboration of the institutional (Section 3.4) and individual-author (Section 3.5) geographic concentration already documented, and — together with the fragmented, nationally siloed co-authorship clusters in Figure 14 — underscores that expanding tropical and Southeast Asian participation (Section 4.6) is not merely a matter of adding new institutions, but of building an entirely new node in the field's global collaboration geography where one has been largely absent to date. Because exact per-country document counts were not exposed in the source visualization, this comparison should be read as a qualitative ranking (China and the United States clearly leading, followed by a broader second tier) rather than as precise, citable figures.

Figure 15. World choropleth map of the geographic distribution of research output by country, Lens.org.

3.13 Summary of Key Bibliometric Indicators

Table 1 consolidates the principal quantitative indicators extracted from Figures 1–15 for quick reference.

Indicator	Value	Year / Rank
Total documents (2010-2025)	17,831	—
Annual growth rate	48.14%	—
Average citations per document	33.94	—
Annual publications (peak)	3,547 documents	2022
Annual publications (2025, rebound)	2,911 documents	2025
Logistic-fit peak year / R^2	2022.4 / 0.849	—
Cumulative saturation ceiling (K)	21,732 documents	Projected
Leading source journal	Sensors (Basel, Switzerland) (~2,970 docs)	Rank 1
Leading institution	Chinese Academy of Sciences (~250 docs)	Rank 1
Leading individual author	Do-Hyeun Kim (~37 docs)	Rank 1
Leading countries by output	China and United States (darkest shading)	Figure 15
Motor themes	IoT/sensors/smart city; IoT/energy efficiency/WSN	Strategic map

4. Discussion

The overall trends of bibliometric evidence indicates that the broader IoT literature relevant to environmental and classroom sensing has undergone rapid, near-exponential growth since 2018, reaching a fitted peak in 2022.4 and an estimated saturation ceiling of 21,732 cumulative documents (Section 3.7). However, such development is not reflected in a strong academic effort devoted to ESP32-enabled heat index sensing for smart classrooms: as illustrated in Fig. 11, through the strategic thematic mapping and Fig. 12, the keyword co-occurrence matrix, concepts relevant to heat index measurement and smart classroom settings are clustered across motor and basic themes nearby (IoT/sensor network, machine learning, ambient sensing) but not explicitly covering heat index. This pattern mirrors findings from other emerging IoT sub-domains, where scientometric analysis has revealed similar fragmentation before a field consolidates around standardized terminology and benchmarks (Ganji & Afshan, 2024; Kim & Wang, 2023).

The journal, institutional and author concentration source-production analysis (Section 3.3) reveals that it is a rather imbalanced publishing system where a single journal - Sensors – receives about 6 times higher contributions than the second leading paper journal. This information, together with top institutions being dominated by Chinese Academy of Sciences as well as several of Asian middle-eastern and European Universities (Section 3.4), reflects a characteristic core-periphery dynamics of any other maturing technology field, with a few venues and institutions defining the critical mass of field-visibility and agenda setting power (Leong et al., 2021; Tanko et al., 2023). This concentration extends to individual researchers: the top five authors alone (Section 3.5) account for a disproportionate share of total authorship credits, a pattern consistent with Lotka's law of scientific productivity, under which a small fraction of authors typically produce a large share of a field's output (Kushairi & Ahmi, 2021).

The co-authorship collaboration network (Figure 14) shows dense collaboration within apparent national or institutional blocs but limited bridging between them — a pattern that, together with the dataset's reported 0% international co-authorship rate, suggests either genuinely siloed collaboration or, more likely, systematic gaps in country-level affiliation metadata within the exported Lens.org records. The recurrence of shared surnames among the leading authors (four of the top twenty share the surname Wang; Section 3.5) further corroborates a collaboration structure organized substantially along national and institutional lines rather than broad international integration. Either interpretation points to the same practical implication: cross-border collaboration in this field is not well captured or well developed, and deliberate efforts to build international, cross-cluster research partnerships particularly linking the dominant East Asian hubs with under-represented tropical regions could accelerate knowledge transfer on classroom heat monitoring specifically.

Under geographic representation gap notably, no Philippine or Southeast Asian institution appears among the ten leading institutions (Section 3.4), despite the region's tropical climate and documented vulnerability to classroom heat stress (De Leon et al., 2024). The choropleth at the country level (Section 3.12; Figure 15) reinforces this absence at a higher level of geographic detail: nearly all of the research work can be seen concentrated in the United States and China, with sparse output across Southeast Asia - illustrating that the relative non-inclusion of Asian institutions is representative of trends across entire countries, not merely due to differences between arbitrary cutoff thresholds (Pan et al., 2012). Unfortunately, this also signifies an area of deficiency in the existing body of evidence that can also be leveraged: the synthesis of cheap, affordable ESP32 hardware expertise with locally validated local definitions of a heat index might allow an underdeveloped niche within an existing area of literature to be filled with a valuable, regionally specific analysis.

A review of current classroom-centric IoT research indicates that most studies focus on measuring temperature and humidity as separate variable (Cañas & Hernández, 2024; Navarrete-Sanchez et al., 2025; Rahmadani et al., 2023; Widjaja et al., 2022), rather than calculating a unified heat-index measure that is tuned to acknowledged standards for thermal stress. In addition, broadly applicable ESP32 heat-index systems have been shown to perform in contexts outside the classroom: in public space monitoring of weather in the Philippines (De Leon et al., 2024), and in automated thermal-comfort control in interior spaces, among others (Cordova Yangali et al., 2024). Thus, the bibliometric review finds evidence that an adequate technological platform is ready cheap ESP32 hardware, well-developed heat-index formulas, established classroom IoT models, and an expanding parent research literature but that these pieces had not yet been tied into a focused research thread for smart classrooms, and that the underlying quality of the bibliographic metadata needs improvement in order to track this emerging specialized domain going forward.

Based on the gaps identified in the bibliometric analysis, several directions are recommended for future research direction, particularly for smart classroom applications in tropical contexts . First, studies should focus on developing and validating standardized ESP32-based classroom sensor nodes capable of computing recognized heat index values, such as those based on NOAA/NWS or Wet Bulb Globe Temperature (WBGT) formulas, rather than relying solely on raw temperature and humidity measurements. Second, future research should integrate lightweight machine learning models into ESP32 heat index monitoring systems to enable predictive heat-stress alerts for teachers, students, and facility managers, thereby supporting proactive classroom management. Third, researchers should investigate the integration of energy-harvesting technologies with ESP32 heat index sensors to facilitate battery-less or low-maintenance, long-term deployments, particularly in schools with limited electrical infrastructure. Fourth, greater research participation from Southeast Asian countries and other tropical regions is needed to develop locally calibrated heat index thresholds and context-specific intervention strategies, addressing the institutional, author-level, and geographic research gaps identified in this study. Finally, future work should establish standardized, open-access datasets containing classroom heat index measurements, complete metadata on institutional affiliations and countries, and corresponding learning outcome indicators. Such datasets would promote reproducibility, strengthen cross-institutional collaboration, and support future bibliometric analyses of the field's development (Donthu et al., 2021).

5. Conclusion

This large-scale bibliometric and knowledge-mapping analysis of 17,831 journal articles published between 2010 and 2025 shows that the field surrounding IoT-based environmental sensing has grown rapidly, is approaching an estimated saturation ceiling of 21,732 cumulative publications, and has matured into recognizable motor, basic, and niche themes — connectivity/sensors/smart city, machine learning, sustainability, environmental monitoring, and biosensing — yet ESP32-based heat index monitoring for smart classrooms has not emerged as a distinct research stream within this landscape. Publishing output is concentrated in a small number of journals (led overwhelmingly by Sensors) and institutions (led by the Chinese Academy of Sciences), and at the individual-researcher level output is similarly concentrated among a small number of highly productive authors led by Do-Hyeun Kim, Rajesh Singh, and Zhong Lin Wang. The co-authorship network reveals collaboration that is dense within national clusters but only weakly bridged across them, and the country-level choropleth confirms that China and the United States anchor global output while Southeast Asia — including the Philippines — remains only lightly represented, with no Southeast Asian institution among the leading contributors despite the region's pronounced exposure to classroom heat stress. The temporal overlay of keyword co-occurrence further shows that the field is moving toward human-centered, well-being-oriented applications, a direction well aligned with classroom heat monitoring but not yet substantially populated by dedicated studies. These findings position ESP32-based heat index monitoring for smart classrooms as a timely and under-researched opportunity, and the five future-research directions proposed in Section 4.6 offer a concrete agenda — spanning sensor design, predictive analytics, energy autonomy, regional and author-level representation, and open, well-documented data — for researchers, particularly in tropical and resource-constrained educational settings, to help close this gap.

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