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Review Article

Adiabatic Techniques in VLSI Design (1992-2024): A 32-Year Bibliometric Review of Trends, Insights, and Future Directions

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Abstract *- The rapid requirement for low-power electronics has increased the interest in adiabatic logic circuits to minimize the energy dissipation in VLSI and low-power computing. Although the literature on different adiabatic logic families and their optimizations continues to grow, to the best of the authors' knowledge, an extensive bibliometric study of this topic remains scarce. This paper aims to provide a systematic analysis of the development of adiabatic logic over the last three decades by exploring underlying research themes, key contributors, and emerging gaps. Bibliometric analysis using Scopus and Web of Science (1992–2024), citation analysis, keyword co-occurrence mapping, and authorship network visualization with the Bibliometrix R package were performed. The findings show a growing number of publications, with an exponential growth in studies after 2000. Although the field's scientific productivity is high, international collaboration still seems limited. The review emphasizes the dominant research themes of energy-recovery approaches and low-power circuit optimization, and identifies what is currently lacking in the integration of adiabatic logic with future computing schemes. This work demonstrates an important concept and methodology for researchers about the importance of interdisciplinary studies and global collaboration in developing energy-efficient semiconductor technologies.*

Keywords *- Adiabatic Logic, Bibliometric Analysis, Energy-Efficient Circuits, Low-Power Electronics, VLSI.*

1. Introduction

With the dominance and rapid advancement of electronic applications, the demand for research and development in electronic circuits and devices has driven the trend toward compact, high-performance, low-power-consumption integrated circuits [1]. In electronic systems, reducing power dissipation improves system performance and capabilities [2], [3], such as switching speed [4], power efficiency [5], and higher performance in high-density circuitry [6]. This compensates for the drawbacks of increased chip density, downsizing, and the increasing complexity of chip power dissipation [7], as well as significant features and issues in VLSI designs [8-11]. Many different low-power optimization VLSI circuit methodologies and strategies have been introduced [12, 13] from the system to the process level. One innovative approach is the adiabatic technique, which leverages thermodynamic principles in low-power VLSI design [13]. Adiabatic logic circuits came forward as a comparatively revolutionary concept in this context. These circuits employ energy-recovery methods to charge and discharge a capacitive load with minimal energy loss. Several studies have utilized the aforementioned technique in various applications, such as IoT [14-22], Biomedical [23], signal processing [24], and low-power designs, in general [25-28]. Based on a comprehensive review of the current literature, there appears to be no existing bibliometric examination of the use of adiabatic technology across various circuits and applications. Hence, this study aims to conduct a comprehensive bibliometric analysis of adiabatic logic circuits and their applications, assessing research trends, influential authors, key publications, and collaboration networks over the past three decades. Like so, in specific to: (1) identify major research themes and track the evolution of adiabatic logic techniques in low-power circuit design through citation and keyword analysis; (2) evaluate the contributions of different countries, institutions, and researchers to understand the research landscape in this field of study; and (3) map emerging topics and research gaps to provide insights into future directions for advancing adiabatic logic and optimizing circuit design strategies.

The first limitation is that the analysis of data obtained from Scopus and Web of Science was conducted, which might have led to the overlooking of significant references and, at the same time, introduced selection bias. Moreover, differences in bibliometric metadata, such as missing or incomplete keyword designations and institutional affiliations, may distort thematic mapping and collaboration analysis. The study's focus is on quantitative measures, including publication counts, citations, and keyword co-occurrence, which is another limitation. It is true that these indicators can illuminate research impact and trends; however, they cannot do that completely, leaving qualitatively important and most likely associated studies unattended. Besides, the analysis period extends from 1992 to 2024; thus, it may not include certain seminal works published before or those that are still not well recognized and do not receive enough citations to be included in the dataset. Finally, the current bibliometric review does not provide empirical support for the claims made in the literature about energy efficiency improvements. Strictly speaking, it is not an empirical investigation.

Both academic and industrial circles can greatly benefit from the results of this research. One of the study's outcomes is that a systematic bibliometric analysis will facilitate the research process by providing a clear understanding of the development, influence, and future direction of research on adiabatic logic circuits. The process of identifying leading research topics and emerging trends not only provides a roadmap for future research but also indicates to scholars the areas that need more attention and helps them focus their research more accurately. Besides that, this research opens the possibility of collaboration among institutions and researchers worldwide by connecting global research contributions and authorship networks, thereby making it easier to establish interdisciplinary and international partnerships. The industry will also be affected by the results, as they align with semiconductor design, VLSI, and low-power electronics.

2. Literature Review

2.1. Adiabatic Logic Families

As one of the most significant research domains influencing the hardware segment of computing, alternative design paradigms, energy recovery approaches, and computational hardware efficiency have reached their limits. Conventional logic gates, which mostly rely on CMOS technology, are constrained by energy-efficiency limitations inherent to their design and operation. These limits have become increasingly apparent as technological advancements have advanced, making it difficult for modern computing systems to consider energy-efficient options. Among them, one very important factor is scaling. The scaling down of dimensions brings traditional MOSFETs that form CMOS logic gates into conflict with one another [29]. On the one hand, miniaturization significantly increases circuit density, but on the other hand, it also entails the devastating consequences of high power consumption and the need for cooling systems that are much larger than the area of the active components. In brief, these factors, when combined, make the energy efficiency issue even more severe in downscaled designs.

Moreover, standard logic gates entail irreversible operations and thus dissipate energy by principle. A more precise argument is provided by the von Neumann-Landauer limit, which implies that energy is lost through the erasure of information during a computational process [30, 31]. So, the traditional schemes are practically confined by that theoretical wall. These difficulties are exacerbated by the high-power dissipation characteristic of CMOS circuits. Such circuits exhibit high static power consumption and dynamic switching losses. All these factors contribute to the inherent inefficiency of conventional logic gates [32-34]. The limited use of power recovery techniques is another problem. For instance, adiabatic logic is a very promising method for recovering power during computation. Yet, even with these techniques, they are still not common in standard CMOS-based designs, which tends to leave conventional logic gates with less-than-optimal energy performance [32-35].

Adiabatic circuits offer a promising option for large-scale, drastic power reduction in electronic systems [36-38]. Adiabatic circuits reduce energy loss by changing the voltage across device resistances very little, thereby performing computations [36]. The switching process is tightly controlled, and a sinusoidal power clock is commonly used in this method to ensure that energy is stored rather than lost as heat [36, 39]. Several logic families have been put forward, each with its own peculiarities and pros and cons, that fall under the adiabatic category. Among such families is TSEL (True Single-Phase Energy-Recovering Logic), which was incorporated in the construction of an 8-bit low-power full adder [36]. The implementation of this procedure achieved 33.1% lower energy consumption than a traditional CMOS full adder [36].

However, the TSEL circuit design had an additional drawback: an oversized circuit area due to the high transistor count, highlighting the trade-off between power consumption and area [36]. Positive Feedback Adiabatic Logic (PFAL) and Efficient Charge Recovery Logic (ECRL) are other families that have drawn researchers' attention and have been investigated extensively [37, 38, 40]. A study comparing PFAL and ECRL NAND and NOR gates implemented in FPGA and ASIC environments found that PFAL logic circuits are notably more power-efficient, especially when using MOSFET transistors for NAND gate applications [37]. In addition, the power dissipated in ASIC implementations of both ECRL and PFAL circuits was lower than that in FPGA implementations [37]. The proper adiabatic family logic ultimately depends on the specific application requirements, with power efficiency, area constraints, and clocking schemes as the main considerations [39]. For instance, selecting a single-phase, 2-phase, or 4-phase power-clocking scheme significantly impacts the circuit's computation time, area, and complexity [39].

2.2. Flip-flops and Sequential Circuits

Many logic-related circuits utilized adiabatic techniques from basic logic circuits (AND, OR, XOR, etc.), such as the presented studies of Gangadhar [5], Sanadhya and Sharma [6], Sharma and Singh [41], and Ganguly et al. [42], which utilized various adiabatic techniques like modified positive feedback adiabatic logic (modified PFAL), Direct Current Diode-Based Positive Feedback Adiabatic Logic (DC-DB PFAL), Complementary Pass transistor Adiabatic Logic (CPAL), among others. Moreover, these techniques can be extended to either half- or full-adder circuits as proposed by Vignesh et al. [7], Ganguly et al. [43], and Vekantesh et al. [44]. Regarding flip-flops, the recent novel design of Sanadhya and Sharma [28], using DC-DB PFAL at different frequencies at a 45 nm technology node based on direct current diodes, demonstrated an 18% reduction in power dissipation and a lower transistor count than related literature. Furthermore, Ng and Lau [45] used the Pass-transistor adiabatic logic with an NMOS pull-down arrangement (PAL-2N) to design SR and JK flip-flops, which were then used to simulate a 4-bit binary counter with 37.6% power reduction.

Hu et al. [46] recommended the use of two-phase Complementary Pass-transistor Adiabatic Logic (CPAL) for developing flip-flops and other clocked circuits due to the minimal number of transistors required and much lower power consumption compared to other adiabatic techniques, particularly the 2N-2N2P technique. Ni and Hu [47] proposed implementing it using a single-phase power clock with a power-gating scheme, achieving about 57.9% power savings in a simulated counter with flip-flops as building blocks. Parveen and Selvi [48] compared D and T flip-flops implemented in 2PASCL and PFAL, with the former consuming less power across the two variations. Moreover, Symala and Srilakshmi [49] synthesized the D flip-flop and 4x1 multiplexer and, compared with CMOS logic, achieved an average of 33–79% power savings and a total of 27–73% savings in area-power product for the designed circuits. Using Improved CAL [50], proposed flip-flops and sequential circuits in TSMC 0.18um CMOS, and reported that, in D flip-flops, energy has been reduced by 14% compared to the conventional CMOS process at 100MHz operation.

Ng and Lau [51] presented a design for SR and JK flip-flops that achieved 87.1% and 89.8%, respectively, in terms of power reduction at 50MHz, which was implemented in a 4-bit binary counter that consumes a noteworthy 97.9uW in 100MHz, or equivalent to 78.5% power saving compared to conventional CMOS. Designing flip-flops can be the building block for more complex chips [52], such as SRAM and microprocessors [53]. Syamala and Srilakshmi [49] utilized the flip-flop in developing and simulating a 4x1 multiplier, resulting in 33-79% power saving. Meanwhile, Celis-Cordova et al. [53] demonstrated, through empirical investigation, that adiabatic microprocessors save energy using 16-bit split-rail charge recovery logic at the 90nm node when operating at 0.5 GHz, compared with a standard CMOS circuit, which consumes much more energy. A standard cell library was also developed for the construction of adiabatic circuits and subsystems. These and similar studies showcased the eminent advantage of adiabatic techniques with branching classifications [54].

2.3. Advanced Architectures

With recent breakthroughs, the application of adiabatic circuits to more complex systems has been broadened. One of the main proofs of progress in the adoption of large-scale systems using superconductor circuits is the successful realization of a microprocessor resembling a RISC architecture (MANA) and a breakout chip for a SHA-3 permutation unit employing AQFP circuits. On the other hand, the development of an AQFP-powered processing unit for convolutional neural networks, or simply CNNs, is a strong indication of the capability of adiabatic circuits in conjunction with high-performance computing and deep learning. A framework for implementing SupeRBNN, or randomized Binary Neural Networks (BNNs) using AQFP devices, has also been introduced, demonstrating remarkably higher energy efficiency than conventional ReRAM-based implementations. Thus, the role of adiabatic circuits in advanced computing applications is being steadily expanded.

Moreover, the use of reconfigurable designs has significantly improved the flexibility and efficiency of adiabatic circuits. The development of a Reconfigurable CPL Adiabatic Gated Logic (RCPLAG) is one example that has resulted in a 4-5% power reduction compared to traditional SCMOS circuits [58]. It is possible to realize both NAND and NOR gates with the same circuit topology and using a single control signal [58]. In the same vein, alterations to PFAL semi-adiabatic circuits have led to an approximate 9% reduction in power dissipation [59]. The continual development of reconfigurable, optimized designs clearly indicates a relentless pursuit to make adiabatic circuits more practical and efficient.

The complexity of adiabatic switching techniques is commonly regarded as a strength, as it enhances their energy efficiency [38]. Researchers have taken several approaches to reduce this complexity. One approach is to introduce asynchronous adiabatic logic, which addresses issues related to clock generation and routing in adiabatic circuits [60]. This method eliminates the global clock signal, thereby simplifying the design and improving performance [60]. Also, progress in complementary pass-transistor asynchronous adiabatic logic has resulted in the drastic reductions in the power consumption (from 50% to 74%) as compared to conventional

CMOS; thus, it can be said that this field has a bright future, especially in the area of asynchronous logic, which tends to be the main beneficiary of the power-saving capabilities of adiabatic logic. The potential advantages of adiabatic circuits have prompted their investigation across diverse applications. In the case of cryptographic computations, which are often power-constrained, especially in smartcards, adiabatic logic can be a potential solution for ultra-low-power operation [61]. The research includes the development of power-efficient Montgomery multipliers using adiabatic logic and the addressing of issues in power-clock generation and gating [61]. The ultra-low-power electronics requirements in passive Near-Field Communication (NFC) systems have driven research into adiabatic logic families [39]. This encompasses the creation of new flip-flops and the deployment of Manchester encoding utilizing adiabatic logic [39]. Moreover, adiabatic circuits have been studied for ultra-low-power arithmetic designs, such as Discrete Cosine Transformations (DCTs) [40].

2.4. Emerging Devices and Materials

The performance and energy efficiency of adiabatic circuits have been considerably improved through the combination of advanced materials and devices. The application of Tunnel FET-Based Adiabatic Logic (TBAL) has resulted in an 80% reduction in energy consumption per cycle compared to conventional CMOS [62]. The architecture leverages TFETs' characteristics and operates efficiently at ultra-low voltages of 0.3 V-0.6 V, resulting in significant energy savings [62, 63]. The illustration of frequency extension at 10 MHz shows the TBAL's potential for IoT applications [62]. Promoting adiabatic circuits, extensive research into materials and designs that yield power-saving circuits, particularly in ultra-low-voltage applications, is essential for their development [63]. The creation of graphene pn-junction-based adiabatic logic gates (INV/AND/OR) is a significant advancement toward ultra-low-power logic gates [61]. This signifies a pivotal shift towards integrating materials and devices linked with energy-efficient adiabatic circuits.

3. Materials and Methods

Bibliometric Analysis is a method based on categories that has been extensively employed to evaluate and analyze academic resources and publications by applying statistical and mathematical methods. Citation indexing, co-authorship analysis, and publication trends are among the techniques used to evaluate the impact and diffusion of research activities [64, 65].

Among the many applications, one of the most important uses of Bibliometric Analysis is that it provides very detailed and clear pictures of research areas by measuring trends, identifying key authors, and recognizing key publications. By doing so, it also illuminates the field's main topics and the directions of its future development. This is exactly where such approaches come in handy for planning upcoming research activities, efficiently and strategically distributing academic resources, and facilitating the formation of collaboration networks. Moreover, the process of analysis is handled by several software packages that are “Publish or Perish”, CiteScape [66, 67], VOSViewer [67], Gephi [68], and Scholarometer [69], which make the analysis challenging but at the same time very effective and efficient.

A thorough search of the databases reveals that none of the previous studies has conducted a bibliometric analysis of adiabatic switching techniques across various circuits and applications. The current section provides a detailed and comprehensive account of the study, which uses data collected from Scopus and Web of Science over the last 32 years (1992 to 2024). Bibliometrix, an R package that provides comprehensive bibliometric analysis and specialized tools for quantitative research in bibliometrics and scientometrics, was used for the analysis [70]. The procedure is divided into data collection, analysis, and visualization.

3.1. Data Collection and Search Criteria

Bibliometric data were obtained from Scopus and Web of Science, widely recognized and comprehensive academic databases in the research community. These platforms are considered suitable for bibliometric analysis because they encompass scientific literature across a wider range of disciplines. A search was conducted on January 4, 2025, using carefully selected keywords and Boolean operators. The search string uses the Boolean operators "AND" and "OR" to query the article titles, abstracts, and keywords. The search strategy, including the exact terms, combinations, and exclusion criteria employed, is detailed in Table 1.

Table 1. Search String

Scopus	WoS
(TITLE-ABS-KEY("Adiabatic switching" OR "PFAL" OR "SCRL" OR "Adiabatic logic" OR "ECRL" OR "Efficient charge recovery logic" OR "Charge recovery logic" OR "Adiabatic logic circuits" OR "SCRL") AND TITLE-ABS-KEY ("CMOS" OR "FinFET" OR "Flip flop circuits" OR "Low power electronics" OR "Sequential circuit" OR "CMOS integrated circuits" OR " VLSI circuits" OR "VLSI" OR "Computer Circuits" OR "Logic circuits" OR "Logic design" OR "Circuit design techniques"))	(ALL=(Adiabatic switching OR PFAL OR SCRL OR Adiabatic logic OR ECRL OR Efficient charge recovery logic OR Charge recovery logic OR Adiabatic logic circuits OR SCRL)) AND (ALL=(CMOS OR FinFET OR Flip flop circuits OR Low power electronics OR Sequential circuit OR CMOS integrated circuits OR VLSI circuits OR VLSI OR Computer Circuits OR Logic circuits OR Logic design OR Circuit design techniques))

It retrieved 953 (Scopus) and 578 (Web of Science) documents, which were the entire records and information that were downloaded, consolidated, and transformed into BibTeX (.bib) format for Bibliometrix version 4.3.0 in RStudio version 2024.12.0+467. R has become more popular among statisticians, data scientists, and researchers than any other tool today because of its extensive array of packages and great support for data manipulation, statistical modeling, and data visualization. Being open-source helps sustain a thriving community that drives the ongoing development of new tools and methods, keeping it one of the leading tools in data science.

Bibliometrix is capable of analyzing three primary groups: (1) authors, which encompasses analysis of the author, their affiliation, and the associated country; (2) publication sources, which can evaluate the influence of sources and confirm productivity; (3) literature, which covers citation information and references [71]. Prior to incorporation and conversion into RStudio, the acquired datasets underwent removal of 380 duplications, resulting in 1151 unique and qualified entries. The metadata quality of the bibliometric dataset was assessed by analyzing missing values in key attributes (Table 2).

The metadata completeness check using Bibliometrix provided very useful insights into the dataset's quality. With no missing entries (0%), several metadata fields, such as Author, Document Type, Journal, Language, Publication Year, Title, Total Citation, Abstract, and Corresponding Author, exhibited outstanding data quality. The areas of research considered here are amenable to bibliometric analysis, thereby enabling accurate assessment of authorship patterns, publication trends, and citation impacts. Metadata fields considered Good were almost entirely complete for data, Cited References (0.26%), Affiliation (1.82%), and DOI (2.52%), indicating relatively high completeness. The gaps are not expected to affect the overall analysis, but they will identify areas that require improvement to enhance the trustworthiness of the dataset. For instance, while affiliation data allows for geographical and institutional analysis, minor incompleteness can limit the scope of regional studies. The same goes for missing DOIs; they can slow document retrieval, which is essential for top-citation network studies. Conversely, fields like Keyword Plus (20.07% missing) and Keywords (22.24% missing) received a Poor rating due to inadequate thematic representation and substantial co-occurrence data.

The above-mentioned drawbacks not only affect keyword mapping and trend analysis but also reduce the extent to which that data is applicable to topic modeling and studies of thematic evolution. The most significant limitation is in the Science Categories field, which is entirely missing (100% missing). This gap makes it impossible to trace disciplinary and interdisciplinary research trends, thereby limiting the already narrow scope of possible analyses. The dataset provides high-quality metadata in key fields essential for conducting basic bibliometric studies. Notwithstanding, the deficiencies in the keyword-related fields and the lack of science categories underscore the need for greater metadata completeness. Closing these gaps would not only enrich the dataset's comprehensiveness but also facilitate multidimensional bibliometric analyses in the future.

Table 2. Completeness of Metadata

Metadata	Description	Missing Count	Missing %	Status
AU	Author	0	0	Excellent
DT	Document Type	0	0	Excellent
SO	Journal	0	0	Excellent
LA	Language	0	0	Excellent
PY	Publication Year	0	0	Excellent
TI	Title	0	0	Excellent
TC	Total Citation	0	0	Excellent
AB	Abstract	0	0	Excellent
RP	Corresponding Author	0	0	Excellent
CR	Cited References	3	0.26	Good
C1	Affiliation	21	1.82	Good
DI	DOI	29	2.52	Good
ID	Keyword Plus	231	20.07	Poor
DE	Keywords	256	22.24	Poor
WC	Science Categories	1151	100	Completely Missing

4. Results and Discussion

4.1. Metadata

The bibliometric analysis, as indicated in Table 3, covers the period from 1992 through 2024 and consists of 1,151 documents from 530 different types of publications, such as journals, books, and others. The annual rate of publication growth is 14.4%, indicating the field’s steady advancement. The age of the documents is, on average, 11.2 years, with an excellent average of 12.69 citations per document, showing how significant these works still are. The dataset included 18,149 references, indicating that extensive research has been conducted on this topic. The dataset showed that the keywords were very popular; the numbers were quite high: 2,897 for Keywords Plus and 2,768 for Author's Keywords. The authorship analysis shows that 2,249 authors contributed to the research, of whom 36 wrote texts as sole authors, totaling 46 such works. The average co-authorship per document is 3.65, indicating strong collaboration. A thorough examination of the document genres reveals that journals are the main source with 581 articles, the next source is conference papers with 495 documents, and other contributions like early access articles (11), proceedings papers (39), book chapters (12), and reviews (13) are added to the total number. The type distribution strongly indicates the vital role of journals and conferences as the primary channels for disseminating research in this field.

Table 3. Main Information about the Data

Description	Results
Timespan	1992:2024
Sources (Journals, Books, etc.)	530
Documents	1151
Annual Growth Rate %	14.4
Document Average Age	11.2
Average citations per doc	12.69
References	18149
DOCUMENT CONTENTS	
Keywords Plus (ID)	2897
Author's Keywords (DE)	2768
AUTHORS	
Authors	2249
Authors of single-authored docs	36
AUTHORS COLLABORATION	
Single-authored docs	46
Co-Authors per Doc	3.65
DOCUMENT TYPES	
Article	581
article; early access	11
article; proceedings paper	39
book chapter	12
conference paper	495
Review	13

4.2. Publication and Citation Trends

Figure 1 and Table 4 provide a visual and tabular representation of the research output trends from 1992 to 2024. In this case, it is very clear that research output has been on the rise, with an evident sudden increase from the middle of the 2000s onwards.

The trend indicates an increase in academic interest in the area, which may be due to technological development, the adoption of new methodologies, or society's growing need for help in solving its problems. The number of publications in certain years, especially 2016 and 2017, has increased sharply.

Most likely, during these years, a large number of articles were written, as they might have corresponded with pivotal research themes or the establishment of professional networks. The average citation per year, however, has not kept pace with this growth, suggesting that the wider academic community engages with these works at a slower rate than their research output. It also indicates that publications might be saturating the market, or the recognition gap is still present in the field. It is revealing that earlier years, such as 1994, had optimal average citations but among the lowest publication volumes, suggesting that the foundations of the discipline may have been laid by a few landmark works in that period.

On the other hand, the recent years have had average citation rates, even though they also have the highest number of publications. This research raises critical questions beyond its quality, impact, and visibility; it also underscores the urgency for the concerned institutions to adopt more effective ways to spread the word and to work together to amplify the impact of their research in the new knowledge area.

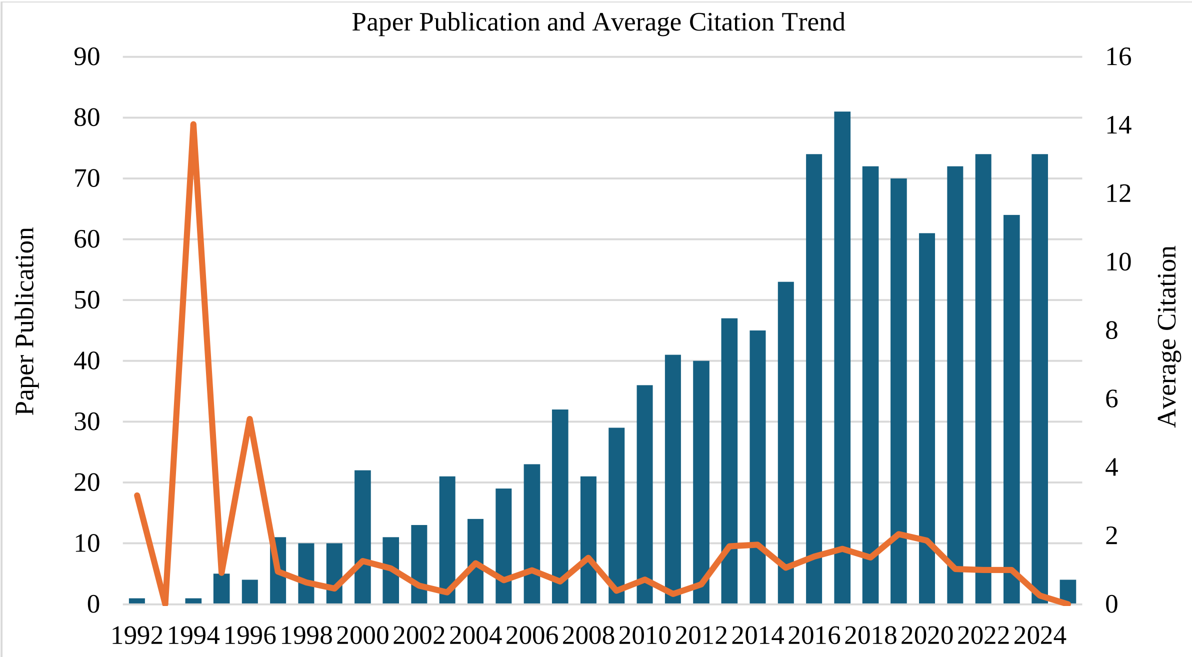

Fig. 1 Publication and Citation Trend from 1992 - 2024

4.3. Countries' Productivity

The analysis confirms the presence of research output and international collaboration. India is the country with the highest number of publications of 193 (23.89% of the total), the majority of which are Single-Country Publications (SCP=186); this is very clear evidence of India's strong preference for domestic publications, which is further supported by the very low MCP ratio of 0.0363. China shows a similar tendency, with an output of 133 articles (16.46), revealing a strong SCP bias (126 articles) and very little foreign collaboration (MCP ratio = 0.0526). Japan's output (134 articles, 16.58%) is slightly more diverse, including 20 participating MCPs and a better MCP ratio of 0.1493, indicating growing interest in joint works. The United States, with 120 articles (14.85%), almost equally splits its contributions between SCP (107 articles) and MCP (13 articles), yielding an MCP ratio of 0.1093. It is also noteworthy that the two countries, Germany (MCP ratio = 0.24) and Canada (0.2667), produce fewer articles (25 and 15, respectively) but still place strong emphasis on international collaboration. On the other hand, all publications from Singapore are domestic, and hence, there are no MCPs, and it exclusively focuses on SCP. Small-volume producers such as Korea (MCP ratio = 0.1613) and Iran (0.1667) exhibit considerable international collaboration relative to their total output. This suggests that countries are implementing multiple strategies at the national level, ranging from full domestic control to establishing an international research network. The list of countries, by number of articles and citations, presented in Table 5, is a really notable part of the differences in research productivity and citation counts across countries. On the contrary, India appears with the highest number of articles, a total of 193, but its citations position is very low with 682, pointing out a huge research output and fewer citations comparatively. The same goes for China, which has little of a gap with 133 articles and is almost equal, but with citations of 650, it is in the territory of these countries, adapting to the visibility or reach of their research outputs. On the other hand, the United States is triumphant with a citation count of 5,127, but it also has a very small contribution of 120 articles, which does not even come close to India, Japan, and China, thus highlighting the research-based nature of the United States. Japan's contribution, on the other hand, comprises 134 articles and 2,237 citations, suggesting balanced performance across articles and citations. Germany, Canada, and the United Kingdom are among the countries with lower output of scientific articles than India, Japan, and China, but their citations are quite high, a reminder of the importance of research quality and the pursuit of impact. The gap between articles and citations highlights differences in national approaches to recognizing research contributions and in modes of research dissemination.

Table 4. Breakdown of Article and Average Citation from 1992 - 2024

Year	Articles Per Year	Average Citation Per Year
1992	1	3.09
1993	0	0
1994	1	13.61

1995	5	0.89
1996	4	5.25
1997	11	0.92
1998	10	0.62
1999	10	0.44
2000	22	1.21
2001	11	1.01
2002	13	0.51
2003	21	0.34
2004	14	1.14
2005	19	0.66
2006	23	0.94
2007	32	0.63
2008	21	1.29
2009	29	0.37
2010	36	0.68
2011	41	0.28
2012	40	0.54
2013	47	1.57
2014	45	1.60
2015	53	0.98
2016	74	1.26
2017	81	1.46
2018	72	1.22
2019	70	1.79
2020	61	1.59
2021	72	0.86
2022	74	0.80
2023	64	0.75
2024	74	0.17

Table 5. Top 10 Countries in terms of Total Articles and Total Citations

Country	Total Articles	Rank	Country	Total Citations
India	193	1	USA	5127
Japan	134	2	Japan	2237
China	133	3	India	682
USA	120	4	China	650
Korea	31	5	Korea	552
Germany	25	6	Canada	495
Singapore	23	7	United Kingdom	381
Iran	18	8	Germany	317
United Kingdom	18	9	Singapore	177
Canada	15	10	Italy	160

4.4. Authors' Productivity

Figure 2, along with Table 6, provides a concise representation of the authors' contributions in this area and their citation performance. While the figure shows the historical publication records of major authors such as Yoshikawa N, Takeuchi N, and Hu J, it also indicates that the researchers remained persistent over a long period. Takeuchi N, in particular, has a very powerful and stable output with a very high total number of citations every year. This is interpreted as a high-impact contribution. In contrast, authors such as Thapliyal H and Ayala C have produced fewer but more impactful publications, indicating that they When it comes to affiliations, the Bibliometrix output indicates that the very first place is occupied by Yokohama National University, contributing 229 articles, which is far more than any other university, for instance, Ningbo University (145 articles) and Nanyang Technological University (43 articles), which shows the latter's leading position in the research area. The participation of institutions like the National Institute of Advanced Industrial Science and Technology (30 articles) and

Japan Science and Technology Agency (27 articles) has made the Japanese institutions' presence even stronger, along with the USA's participation, for instance, the University of Maryland and the University of Kentucky. The research effort is worldwide; however, the few key institutions' dominance indicates a concentration of academic power that could be easily addressed by international collaboration for diversity in contributions.

Table 6. Most Local Cited Manuscripts

Rank	Author	Year Published	Journal Information	Citation Frequency
1	Moon Y	1996	IEEE J SOLID-ST CIRC, V31, P514, DOI 10.1109/4.499727	127
2	Athas W. C.	1994	IEEE TRANSACTIONS ON VERY LARGE SCALE INTEGRATION (VLSI) SYSTEMS, V2, P398, DOI 10.1109/92.335009	91
3	Takeuchi N	2013	SUPERCOND SCI TECH, V26, DOI 10.1088/0953-2048/26/3/035010	90
4	Likharev KK	1991	IEEE T APPL SUPERCON, V1, P3, DOI 10.1109/77.80745	77
5	Mukhanov OA	2011	IEEE T APPL SUPERCON, V21, P760, DOI 10.1109/TASC.2010.2096792	64
6	Herr QP	2011	J APPL PHYS, V109, DOI 10.1063/1.3585849	63
7	Dickinson AG	1995	IEEE J SOLID-ST CIRC, V30, P311, DOI 10.1109/4.364447	60
8	Takeuchi N	2017	SUPERCOND SCI TECH, V30, DOI 10.1088/1361-6668/AA52F3	60
9	Oklobdzija VG	1997	IEEE T CIRCUITS-II, V44, P842, DOI 10.1109/82.633443	56
10	Takeuchi N	2015	J APPL PHYS, V117, DOI 10.1063/1.4919838	54

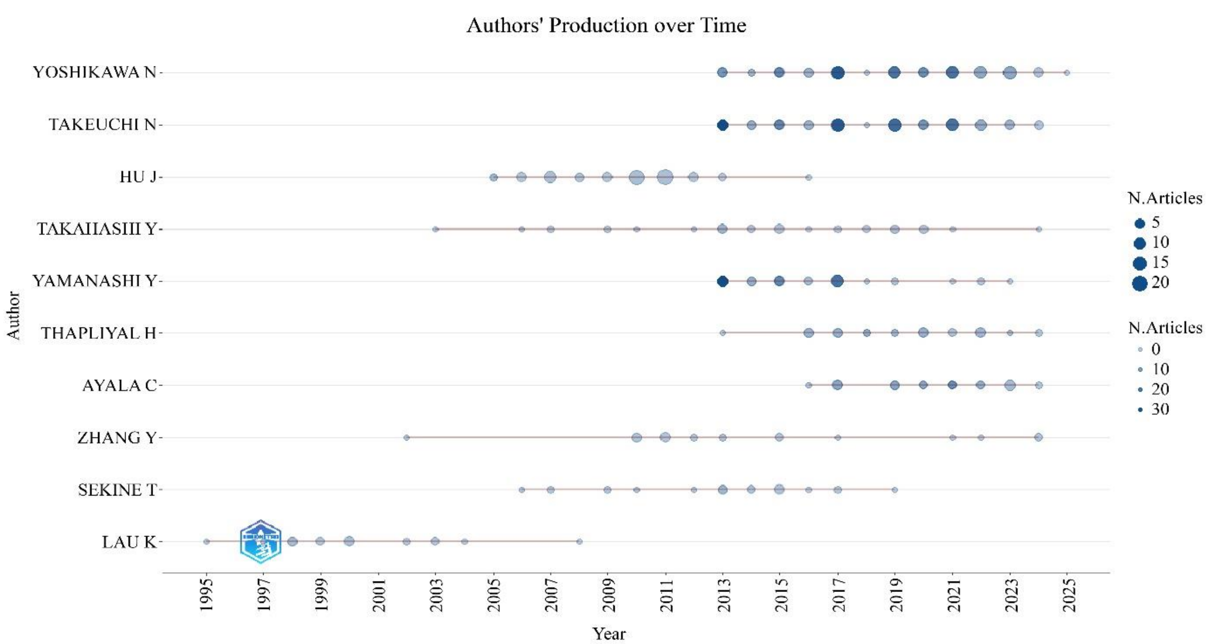

Fig. 2 Authors' Production over Time

4.5. Lotka's Law

The assessment of Lotka's Law coefficient estimates provides important information about the allocation of productivity between the authors in the database. The beta coefficient estimate of 1.748531 indicates an which a small number of writers produce a large share of publications. This, therefore, aligns with the typical observation across academic fields: a handful of very productive scholars are responsible for the majority of publications, while most researchers contribute little. The constant of 0.2022409 indicates that about 20.2% of authors contributed only one article, highlighting that research output is concentrated among a small group of highly productive researchers. The other side of the goodness-of-fit value (0.855776) indicated the conformity of Lotka's Law to the observed data and thus supported its application to this dataset.

The Kolmogorov-Smirnov two-sample test yielded a p-value of 0.05623007, which is greater than the 0.05 threshold, indicating that the actual distribution is not substantially different from the theoretical distribution. Lotka's Law applies to the dataset, revealing disparities in authors' research productivity.

Table 7. Lotka's Law uneven distribution of authorship, consistent with Lotka's Law, in coefficient estimation

Parameters	Value
Beta Coefficient Estimate	1.748531
Constant	0.2022409
Goodness of fit	0.855776
P-value of the Kolmogorov-Smirnov two-sample test	0.05623007

4.6. Thematic Maps

In Figures 3-5, the main research directions in energy-efficient electronics are presented as thematic clusters and their connections. The research is categorized by the thematic map into Motor Themes (e.g., "adiabatic logic," "CMOS integrated circuits," "logic circuits") that are heavily studied and are also the most important in the field, serving both industry and academia.

Basic Themes include "charge recovery logic" and "power," which remain quite abstract and require further specification. Niche Themes such as "logic design" and "capacitance" represent areas that are modern and inventive but are not yet fully integrated into the general knowledge and practice. The Emerging or Declining Themes (e.g., "logic devices") are, on the other hand, showing either the very beginning of research or the disuse of interest.

The co-occurrence network places the topics of "computer circuits," "adiabatic logic," and "low-power electronics" very highly, as they are all tightly interlinked and of the highest interest.

All these themes work together to address problems in energy efficiency, power dissipation, and circuit optimization. Niche subjects such as "charge recovery logic" offered specific solutions to certain problems but did not reach a prime location in the central research network, as they were mainly peripheral and connected to the core area.

The word cloud provides a clear view of the most important terms, such as "computer circuits" and "CMOS integrated circuits," as well as new terms like "reconfigurable hardware" and "adiabatic switching." This suggests that basic and artistic designs are being developed towards energy-efficient design. To conclude, this analysis uncovers a vibrant research environment that is effectively addressing the core issues of energy-efficient electronics while developing new technologies and methods. The Multi-Dimensional Scaling (MDS) conceptual structure map shown in Figure 6 provides a clear view of the individual research areas in energy-efficient electronics, organized by their similarity in terms of connections and themes.

The first area is at the core of the issues to be examined and includes terms such as "logic gates," "adiabatic circuits," "low power electronics," "integrated circuit design," and "computation theory." These highly correlated areas are the main reason for the best circuit performance with the least power loss, which is an effective logic design factor in electronic systems.

The second bloc investigated factors related to circuits and power optimizations, as it has themes like "adiabatic logic," "VLSI circuits," "low power," and "power". This group emphasizes the use of advanced technology in circuits for energy savings and the creation of technical infrastructure for power management and scaling in consumer electronics. On the other hand, the third group is more focused on energy saving and utilization, the group discussing themes "energy efficiency," "energy utilization," and "feedback."

This group is advocating the strategies connected to the optimization of energy consumption and the idea that the use of energy is more practical than merely improving logic optimization. The fourth portion is linked to recently invented techniques related to "charge recovery logic" and "recovery." These topics address energy loss, introducing new techniques rather than new methods at the circuit level, but do not fully cover larger research themes.

The thematic connections of the clusters are shown in their spatial distributions, with basic themes in the middle and links to advanced design techniques and broader energy-saving methods. The research considers the balancing of basic research with creative techniques and application-oriented strategies as the main issue. In addition, it reveals the directions where further investigation into energy-efficient electronics can be done.

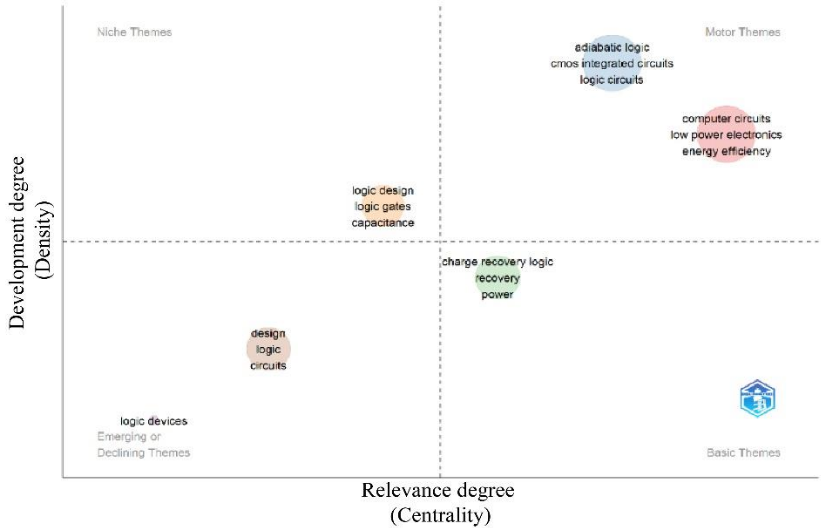

Fig. 3 Thematic Map

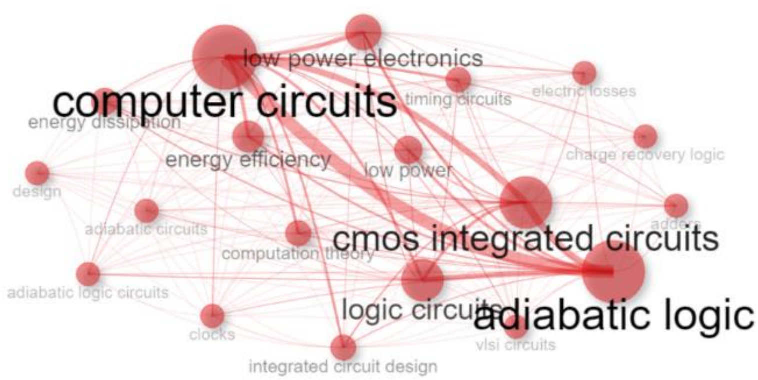

Fig. 4 Co-occurrence Network

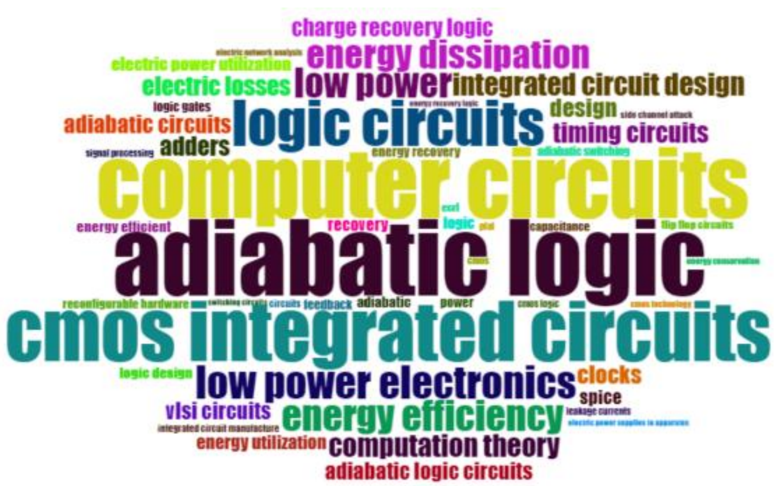

Fig. 5 Word Cloud

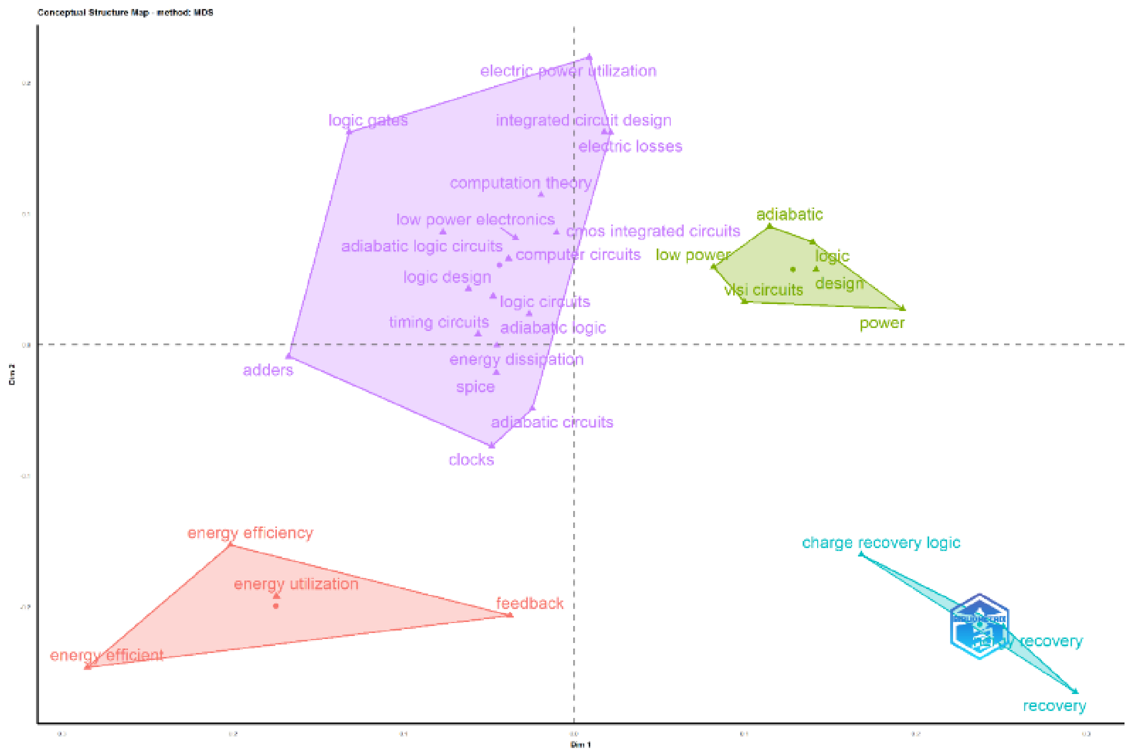

Fig. 6 Conceptual Structure Map

5. Conclusion

This research article presents an in-depth bibliometric study of adiabatic logic circuits, tracing their development, major contributors, and emerging research directions over the last 30 years. The results indicate that scientific output has grown steadily, with the most significant increase in research interest occurring in the mid-2000s, suggesting that the importance of energy-efficient electronic design is increasingly recognized. The authors of this paper employ citation network analysis, keyword mapping, and authorship collaboration metrics to highlight the main research themes, the top institutions, and the geographic distribution of research in the field. One interesting observation is that although the research output is very large, the number of international collaborations remains quite small; thus, there is a great opportunity to strengthen global partnerships, which would lead to faster progress in adiabatic logic.

The implications of this study extend across multiple dimensions. Theoretically, it strengthens the position of energy recovery methods in circuit design by providing a systematic overview of the main innovations and their effect on computational efficiency. On the other hand, the practical implications could serve as a roadmap for researchers and industry professionals to develop less power-consuming electronic devices by focusing on the areas of cryptographic circuits, IoT, and HPC, which are most affected by this. This research, though vast in its implications, has some limitations. The choice of Scopus and Web of Science databases, though exhaustive, might narrow the study's corpus by excluding important literature from non-mainstream sources. The use of citation and publication trend methods to measure the impact of the research might also not accurately reflect the research's main impact. Future studies are expected to use a larger dataset and a qualitative methodology for research evaluations, as well as to examine adiabatic circuit designs through experimental verification.

Based on these conclusions, the next step in research should be to focus on interdisciplinary partnerships and the use of new materials and device architectures to increase the scalability of adiabatic logic circuits.

Besides, the thorough investigation of hybrid energy-efficient computing paradigms might open up a new area in low-power electronics, such as neuromorphic and quantum-inspired architectures. Addressing these challenges will be instrumental in transitioning adiabatic logic from theoretical exploration to practical, high-performance commercial implementation.

Conflicts of Interest

The author(s) declare that there is no conflict of interest regarding the publication of this paper.

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