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Assessing the contribution of semiconductors to the sustainable development goals (SDGs) from 2017 to 2022

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ABSTRACT

Semiconductor development is a major driving force for global economic growth. However, synchronizing it with the Sustainable Development Goals (SDGs) set by the United Nations remains a critical challenge. To gain insight into this, we analyzed SDG-related publications on semiconductors from 2017 to 2022 using the SciVal database. The study found 77,706 documents related to SDGs in the field of semiconductor research, with an overall increase in the number of publications each year. The main focus of these publications was SDG 7 (Affordable and Clean Energy), accounting for 68.9 % of the total publication count. Additionally, the results indicate that semiconductors have multifaceted potential in advancing a range of SDGs. From fostering innovations in healthcare (SDG 3), ensuring clean water access (SDG 6), catalyzing transformative industrial growth (SDG 9), to contributing to climate mitigation strategies (SDG 13), semiconductors emerge as versatile drivers of sustainable development. The respective publication percentages for these goals were 7.3 %, 5.9 %, 9.7 %, and 4.4 %, underscoring their capacity to make substantial contributions across various facets of sustainability. It's worth noting that only 2.9 % of these publications stem from academia-industry collaborations. This indicates a pressing need to facilitate collaboration between academia and industry, as such partnerships have the potential to amplify the impact of semiconductor innovations on the SDGs. The novelty of this study lies in its specific exploration through a comprehensive analysis spanning five years, revealing the alignment between semiconductor advancements and the latest SDGs. It uncovers the significance of collaborative ecosystems involving research institutions, businesses, and governments. Through these results, our study addresses a gap in the existing literature and advances semiconductor contributions to the SDGs.

1. Introduction

The rapid growth of the semiconductor industry has intensified competition in a global industry where leading-edge technology and economic development are intertwined. Statistics from the Semiconductor Industry Association (SIA) reported that global

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semiconductor sales grew by 6.5 % (∼US$43.9 billion) in 2020 compared to 2019 [1], and by 26.2 % in 2021 (>US$55 billion) [2], In 2022, Taiwan was ranked 21st in the world in terms of [1]gross domestic product (GDP 3.3 %), up from the prior year [3], with the semiconductor industry being a key economic driver. The annual output value of semiconductors in the manufacturing industry in Taiwan reached 2.465 billion in 2022, with a growth rate of 32.2 %, and this figure is growing [4].

Can semiconductors play a role in achieving the United Nations 2030 Sustainable Development Goals (SDGs)? Several international conventions, such as the Clean Air Act (which aims to protect air quality by regulating emissions of air pollutants to ensure clean air for the public), the Basic Environment Act (focused on ensuring the sustainability of the natural environment and the protection of ecosystems and biodiversity), the Paris Agreement (a global climate accord designed to limit global temperature rise by reducing greenhouse gas emissions to address climate change), and the Carbon Neutrality Declaration (a commitment to balance carbon emissions with carbon removal or offset measures to combat climate change), have been developed to address issues related to the depletion of Earth's resources, the greenhouse effect, and carbon emissions [5–10]. The United Nations introduced the 2030 SDGs in 2015, encompassing 17 core objectives ranging from eradicating poverty to enhancing global health, and education, addressing climate change, and preserving ecosystems worldwide [10]. Therefore, semiconductors can boost a country's economic fortunes, it is critical that they also contribute to achievement of the SDGs.

Semiconductors are indispensable in our daily lives, they are crucial components in the development and production of electronic devices, enhancing efficiency and driving various industries. It enables the miniaturization of electronic chips while delivering high performance, making end products more energy-efficient and affordable for everyone [11–13]. The advancements in semiconductors drive technological innovations such as electronic communications, artificial intelligence, machine learning, automation, and the internet [14–17], enhancing our lives in numerous ways. They also contribute to improving medical equipment and accelerating scientific research, ultimately increasing societal health and well-being [18,19]. Furthermore, semiconductors play a significant role in smart automation, reducing energy wastage, and supporting global internet and communication systems. From these contributions, it seems that semiconductors are indeed helping to advance the SDGs.

However, in the pursuit of these contributions, the semiconductor industry may also have negative environmental impacts, including substantial water and energy consumption. The [3]Taiwan Semiconductor Manufacturing Company Limited (TSMC) report indicates that total water consumption in 2020 was 77.3 million metric tons. Compared to the average daily water consumption of 289 L per person in the same year, this is equivalent to the water consumption of approximately 7.3 million people [20,21]. Such results indicate that the semiconductor industry must address their water use and wastewater treatment processes. Furthermore, semiconductor companies use specialized equipment for [4]extreme ultraviolet lithography (EUV) to produce the latest advanced microchips. ASML report stated that a next-generation EUV lithography machine consumes approximately 1 MW (megawatts) of power [22]. *McKinsey on Semiconductors* revealed that a fab's annual electric energy consumption equals that of about 50,000 households. Semiconductor wafers are manufactured using various chemicals, which generate high-global warming potential (GWP) greenhouse gases [23,24]. With these critical and irreplaceable processes, the semiconductor industry continues to increase its energy consumption, making it vital to explore how semiconductors can reverse this trend and contribute responsibly to sustainable development.

This article aims to explore the role of semiconductors in attaining the SDGs by analyzing research publications related to semiconductors and SDGs from 2017 to 2022. Through a survey of 77,706 documents gathered from the SciVal database, we seek to understand how semiconductor research aligns with the SDGs and identify research directions that promote sustainable semiconductor development.

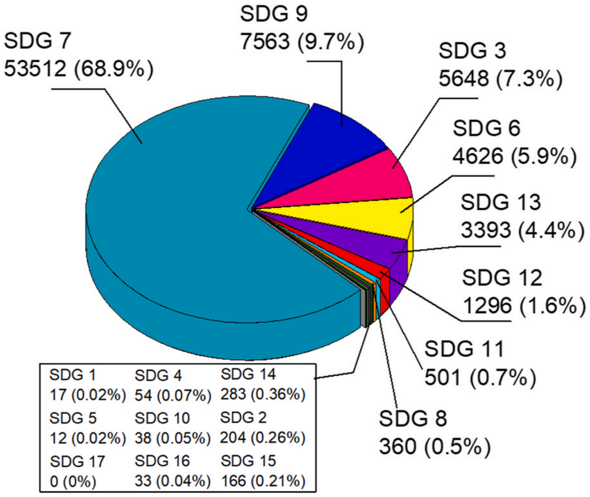

Fig. 1. Number of semiconductor-related publications from 2017 to 2022 by SDG program.

2. Results

2.1. Volume, growth trajectory, and geographic distribution of semiconductor and sustainable development literature

A total of 77,706 documents on semiconductors and SDGs were retrieved from SciVal, as shown in Fig. 1. The pie chart shows that the SDG category with the largest number of semiconductor-related publications is SDG 7 - Affordable and Clean Energy (53,512 documents), accounting for 68.9 % of the total. This is followed by SDG 9 - Industry, Innovation and Infrastructure (7563 documents) and SDG 3 - Good Health and Well-being (5648 documents). These results suggest that the global research trend on semiconductors centers around SDG 7.

The total number of semiconductor- and SDG-related publications from 2017 to 2022 was analyzed (Fig. 2). Results clearly demonstrate that the top five goals, namely SDG 7, SDG 9, SDG 3, SDG 6 and SDG 13, show a steady upward trend in research volume on a yearly basis. Among them, SDG 7 has the largest number of published documents (53,512), including articles (49,109, 91.77 %), reviews (3,273, 6.12 %), editorial materials (18, 0.03 %), letters (46, 0.09 %), and others (1066, 1.99 %). The cyan bar for SDG 7 (Fig. 2) shows that the number of publications exceeded 6000 in 2017 and increased to over 8000 in 2018, representing an increase of ~30 %. The number of SDG 7 publications exceeded 9000 from 2019 to 2021, and increased to over 10,000 in 2022. Fig. 3 reflects the distribution of SDG 7-related publications in different countries. The darker the color, the higher the number of publications in that region. As shown in the figure, SDG 7-related research on semiconductors spans Asia, Europe, North America, South America, and Oceania, with Asian countries more actively conducting this research.

Table S1 displays the top 15 countries with the most productive and influential research output. The top three countries based on Total Publication (TP) ranking are China (22,198), the US (7,520), and India (5,650). A total of 1503 documents were published in Taiwan. The Total Citation (TC) ranking reveals that China (538,409), the US (195,524), and South Korea (68,786) are the top three countries. Taiwan (22,260) is ranked 15th for research impact. These findings indicate that global research efforts are serious about the importance and urgency of SDG-related semiconductor issues, and are not simply focused on advancing semiconductor technology.

The top 50 % keywords in the SDG 7-related results were further examined through a word cloud (Fig. 4), with results indicating the most common keyword combinations were *solar cell*, followed by *quantum dot*, *perovskite solar cell*, *light emitting diode*, and *layered semiconductor*. Since SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all, these keywords show the high relevance of semiconductor research toward promoting sustainable energy.

2.2. Semiconductor contributions to SDGs 7

Based on these results, the impact of semiconductors on SDG 7 was analyzed in more detail and the top 10 documents in the FWCI ranking for semiconductor publications are summarized in Table 1. These publications show that the goal of SDG 7-related semiconductor development is devising clean energy applications. From the perspective of semiconductor materials, they encompass a variety of categories, including silicon-based Semiconductors (a-Si:H, SiC, SiGe, SiN) [25–28], metal oxides (TiO_2, ZnO, SnO_2) [29–31], organic materials (Polythiophenes, Polythiophenes) [32,33], inorganic crystal semiconductors (II-VI: CdS, CdTe, III-V: GaP, InAs, GaAs, GaN) [34,35], semiconductor composite materials (perovskite) [36], and transition metal dichalcogenide (MoS_2) [37]. These are garnering significant attention due to their versatile properties, such as tunable bandgaps, unique optical characteristics, and electron transport capabilities. These properties confer unique advantages to semiconductor materials in the fields of science and engineering. Among these materials, as demonstrated by SDG 7-related publications, perovskite materials have made groundbreaking advancements as alternatives to traditional silicon-based solar materials.

According to the literature report, perovskite materials exhibited a remarkable increase in power conversion efficiency (PCE) for solar cells between 2009 and 2020, rising from a mere 3 % to over 25 % [36,38]. This achievement can be attributed to meticulous

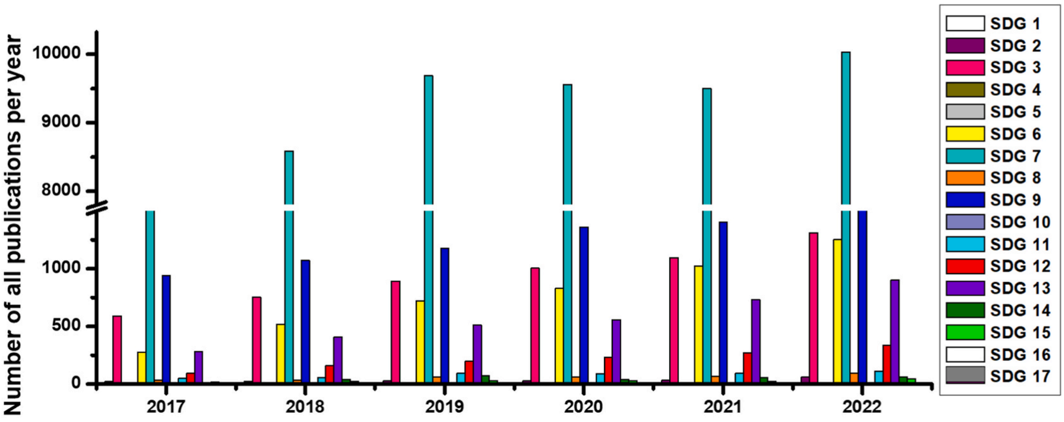

Fig. 2. Number of SDG-related publications on semiconductors per year from 2017 to 2022.

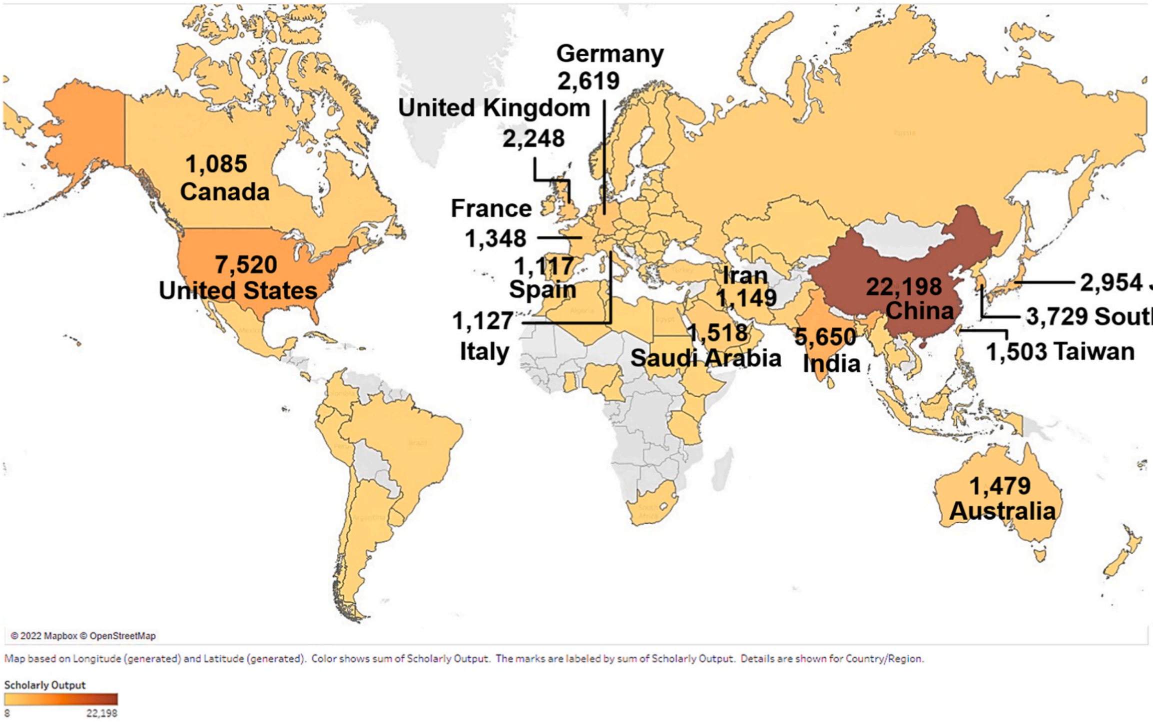

Fig. 3. Countries contributing to SDG 7-related publications from 2017 to 2022.

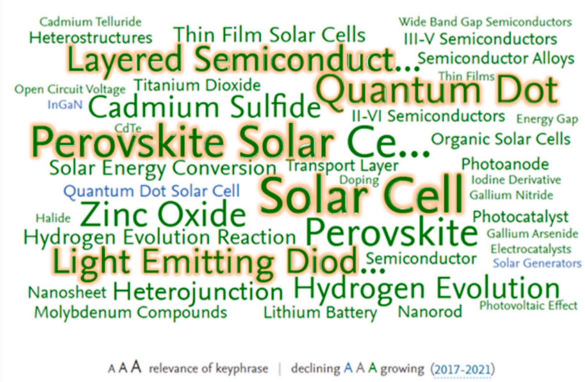

Fig. 4. Word cloud for keywords in SDG 7-related publications on semiconductors.

defect engineering in perovskite films, specifically addressing anion vacancy defects.

Furthermore, the literature analysis identified the broad prospects of semiconductor materials in various fields, including hydrogen production and electronic devices. From the perspective of semiconductor applications beyond solar energy, there has been a growing global demand for clean, zero-carbon energy sources, as evidenced by the 94 million-tonnes hydrogen demand in 2021 [39], as reported by the International Energy Agency (IEA). This demand has sparked extensive research efforts that harness semiconductor materials to enhance hydrogen production using methods such as photocatalytic [40,41], electrocatalytic, and photoelectrochemical reactions [42,43]. For instance, the formation of heterojunctions between materials like tungsten oxide (WO) and porous nitrogen-doped carbon significantly enhances hydrogen production efficiency [44]. Modification of molybdenum disulfide (MoS_2) with ruthenium nanoparticles, coupled through sulfur sites, demonstrates the potential for enhancing hydrogen evolution electrocatalysis [37]. Additionally, modification of bismuth vanadate ($BiVO_4$) with hydroxyl iron (FeOOH) or carbon doping has demonstrated improved photoelectrochemical stability and hydrogen production efficiency [45,46]. Furthermore, advances in material optimization, utilizing high-performance core-shell micro-wire pn heterojunctions developed with conductive polymers (polyaniline) and semiconductor metal oxides (ZnO), have facilitated effective charge carrier transfer, thereby enhancing electronic applications [47]. These diverse researches highlight substantial progress in semiconductors and their transformative applications in advancing

Table 1
Summary of the semiconductor analyses for various SDG 7-related applications.

Type	Materials	Main findings	Year	Ref
Solar cell	Metal halide perovskite (α-$FAPbI_3$)	With the concept of anion engineering, anion vacancy defects existing at grain boundaries and the surface of the perovskite film are suppressed to increase the crystallinity of the film and achieve a 25.6 % power conversion efficiency of solar cells.	2021	[36]
Solar Cell	n-type organic semiconductor, non-fullerene acceptor molecule	Design of novel non-fullerene n-type organic photovoltaics with electron-deficient cores to achieve 15 % power conversion efficiency of solar cells.	2019	[69]
Light-emitting diodes	$CsPbBr_3$/MABr quasi-core/shell structure perovskite	Development of visible perovskite light-emitting diode (PeLED) with over 20 % quantum efficiency.	2018	[70]
Hydrogen production	2D porous carbon nitride (PCN) 1D $W_{18}O_{49}$ (WO)	Achievement of photocatalytic hydrogen generation capability by increasing electron transfer at the 1D WO/2D porous carbon nitride heterojunction interface and increasing catalytic active sites in porous structures.	2022	[44]
Photoelectrochemical water oxidation	FeOOH-modified defective $BiVO_4$ quantum dots (QDs)	Development of FeOOH-modified defective BiVO4 photoanodes to optimize the photoelectrochemical stability of BiVO4 photoanodes during water oxidation.	2022	[45]
Organic/inorganic heterojunction photodetector	PANI/ZnO core-shell microwire	Application of chemical vapor deposition technology to prepare PANI/ZnO core-shell microwire heterojunctions, which have potential for use as high-performance rectifier switches.	2022	[47]
Hydrogen production	carbon doping of $BiVO_4$ QDs	Use of carbon doped-BiVO4/CQDs dual carbon composite materials for applications in photoelectrochemical (PEC) hydrogen generation.	2022	[46]
Light-emitting diodes	Organic-inorganic hybrid perovskite ($MAPbBr_3$)	Use of long-chain ammonium cations to increase the stability of perovskite nanocrystalline light-emitting diodes (LEDs).	2017	[71]
Hydrogen evolution reaction (HER)	Ru–MoS_2	Use of Ru nanoparticles coupled to S sites at MoS2 interfaces to increase hydrogen evolution electrocatalysis.	2022	[37]
p–n heterojunction photocatalysts	p-type and n-type semiconductors	Use of different semiconductor heterojunction photocatalysts to modulate the interfacial energy band arrangement between different semiconductors, promote the spatial separation of photogenerated electron-hole pairs, and enhance the photocatalytic activity of carbon reduction or hydrogen generation.	2017	[72]

SDG 7, ultimately leading to enhanced energy efficiency through innovative approaches. The significant progress in semiconductor research in advancing SDG 7 aligns seamlessly with trends promoted by other literature, such as pre-combustion carbon capture [48], solar thermal systems [49], and biogas utilization [50]. These diverse sectors collectively focus on achieving SDG 7 and promoting clean, affordable energy solutions.

Moreover, the importance of semiconductor surfaces and interfaces are also demonstrated in the literature excerpts listed in Table 2. From the top 10 published journals for SDG 7, *ACS Applied Materials & Interfaces*, a multi-disciplinary journal for the study of materials and interfaces, tops the ranking with respect to the number of publications and citations, followed by *International Journal of Hydrogen Energy, Journal of Materials Chemistry A*, and *Applied Surface Science*. Specifically, ACS Applied Materials & Interfaces has published 1446 articles and received 35365 citations, indicating its leading position in semiconductor research. International Journal of Hydrogen Energy closely follows with 1067 articles and 18751 citations. Journal of Materials Chemistry A and Applied Surface Science have 989 and 984 publications respectively, with 36882 and 21131 citations each. These findings emphasize that addressing the surface and interfaces of materials using semiconductors as a sustainable material is essential and decisively impacts overall performance.

SDG 7-related data shows that 97.1 % of this research comes from academia, as shown in Table 3. Only 2.9 % was published through research-industry collaborations, indicating that the largest contributors to SDGs are still academic scientists. Nevertheless, some semiconductor companies are actively engaged in promoting SDG 7. Further analysis reveals that among the top 50

Table 2
The top 10 journals for SDG 7-related publications on semiconductor research.

Scopus Source	Publications	Citations	Authors	Citations per Publication
ACS Applied Materials & Interfaces	1446	35365	9231	14.4
International Journal of Hydrogen Energy	1067	18751	4940	10.0
Journal of Materials Chemistry A	989	36882	6184	21.0
Applied Surface Science	984	21131	5162	12.0
Journal of Alloys and Compounds	969	13450	5378	96
Solar Energy	738	10466	3330	11.0
ACS Applied Energy Materials	737	9304	4746	8.4
Journal of Physical Chemistry C	718	10639	3745	7.0
Chemical Engineering Journal	683	19350	4392	19.4
Journal of Materials Science: Materials in Electronics	583	3666	2537	4.2

Table 3
Scholarly output on SDG 7-related semiconductor research with both academic and corporate author affiliations.

Collaboration		Total publications	Citations	Field-Weighted Citation Impact
Academic-corporate collaboration	2.9 %	1598	28639	1.52
No academic-corporate collaboration	97.1 %	51914	941804	1.62

semiconductor companies engaged in collaborative publications (Table S4), these semiconductor companies come from various countries. This includes France (2 companies), South Korea (4 companies), the United States (7 companies), Switzerland (4 companies), Germany (5 companies), Japan (8 companies), China (9 companies), Italy (1 company), Finland (1 company), Saudi Arabia (1 company), Norway (1 company), Taiwan (3 companies), Netherlands (2 companies), Canada (1 company), and United Kingdom (1 company). The global distribution of semiconductor companies participating in academic collaboration research underscores their international involvement and diversity. They encompass regions such as Europe, North America, and Asia. These companies from different countries have collectively contributed to advancing SDG 7 through collaborative research.

2.3. *Semiconductor contributions to other SDGs*

Through literature analysis, it becomes evident that the semiconductor industry is actively driving multiple SDGs, playing a pivotal role. The semiconductor industry requires innovative research and optimized industrial process technologies to facilitate SDG 9, which aims to build disaster-resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. More specifically, the current semiconductor industry consumes significant amounts of energy and water, making SDG 9 a critical goal. Researchers are constantly seeking new ways to address industrial wastewater and related process improvements. For example, newly developed ceramic nanofiltration membranes adsorb organic matter and heavy metal ions from wastewater to reduce wastewater contamination [51,52]. Biomass sources (biochar) combined with surface modification technologies remove heavy metal ions from water [53]. Solar desalination produces clean water to address water scarcity [54]. Semiconductor materials are combined with 3D printing technology as 3D electrodes for capacitive material applications [55]. Under SDG 9, scientists are laying the groundwork for research and development and innovation, providing strategies to industry toward achieving environmental sustainability.

Semiconductors have also been shown to contribute to both SDG 3 and SDG 6, as they are widely used for detecting and degrading environmental pollutants such as volatile organic compounds (VOCs) and water pollution (heavy metals, organic dyes, antibiotics). Similarly, they contribute to the biomedical field with applications in bioimaging [56], virus/bacterial tests (SARS-CoV-2) [57], and cancer cell detection [58]. This offers companies more ways to give back to society, ensure social health and safety, and improve social well-being.

3. Discussion

Based on the above results, it is evident that the semiconductor industry continues to contribute to the achievement of the SDGs. From the perspective of research trends and priorities in the semiconductor industry related to SDGs, the prominent role of semiconductors in SDG 7 research can be seen as a manifestation of the global commitment to sustainable development. Most semiconductor-related research aligns with SDG 7, with a strong emphasis on solar and hydrogen energy, driven by materials such as perovskites and zinc oxide, known for their high efficiency and low cost. While research in other SDG areas is relatively less (less than 10 %), there is a growing trend in the annual publication output related to semiconductors over time. Therefore, there remains significant potential for development in these areas, particularly in SDG 9 (promoting innovation and sustainable industrialization). These research topics include applications in the Fourth Industrial Revolution (Industry 4.0) [59,60], and machine learning for diagnosis in manufacturing systems [61,62], all of which reflect the pursuit of more efficient, environmentally friendly, and sustainable manufacturing processes.

Moreover, semiconductors also have a significant impact on SDG 3 (ensuring healthy lives and promoting well-being). The field is gradually advancing the application of semiconductor technology in medical devices and health monitoring. For instance, semiconductor components can be used in biosensors capable of tracking patient physiological data and providing real-time health monitoring [63,64]. This is crucial for disease prevention and early diagnosis, contributing to improving the quality of people's social lives and health. Semiconductor materials can also harness their photoelectric properties to expand SDG 6 by utilizing advanced sensing technologies such as advanced oxidation processes [65], photocatalysis [66], and electrocatalysis [67] for the further improvement of environmental water resources and restoration. These topics reflect the semiconductor current emphasis on technological innovation, medical advancements, and environmental concerns, which are globally prioritized issues.

4. Challenges and future research directions

Based on the literature and content analysis, we can return to the fundamental question: can semiconductors help advance the SDGs? The answer is yes. From an academic perspective, the number of semiconductor-related articles promoting SDGs is enormous, covering advancements in green energy, energy storage, water restoration, and social health and safety. These various research topics are opportunities for scientists to lay the groundwork for achieving the SDGs. However, in the pursuit of aligning semiconductor technology with the SDGs, it is essential to confront the intricate challenges that lie ahead.

4.1. Resource constraints

The semiconductor manufacturing industry is resource-intensive. This includes significant consumption of electricity, water, and rare materials during the manufacturing process, which, as production scales up, can lead to global resource constraints and pose challenges to environmental sustainability efforts. This concern is particularly pronounced in Taiwan, which has become a focal point for the semiconductor industry. Given its limited natural resources, relying on imported coal and natural gas as primary energy sources, and facing water scarcity, companies must adopt new technologies to reduce energy consumption. Sustainable procurement is a path to business transformation. Companies directly purchase green power and carbon rights, which promotes the SDGs. For example, TSMC and Intel have committed to targets of 40 % and 100 % renewable energy by 2030, respectively. But obviously, more is needed. Taiwan's green energy is in short supply. When companies only compete to purchase sustainable energy, but do not invest in development, longer-term sustainability issues cannot be solved. Therefore, it is recommended to encourage companies to contribute to the development of sustainable energy infrastructure as a way to give back to society. This approach is essential for achieving long-term sustainability goals.

4.2. Semiconductor waste

The rapid pace of innovation in the semiconductor industry results in the frequent obsolescence of electronic devices [68]. This contributes significantly to the growing problem of electronic waste. It has been suggested from the literature that most semiconductor research tends to prioritize material efficiency while overlooking the generation and recycling of waste materials. Within the realm of water treatment journals, there is minimal consideration for the extended waste management issues associated with used semiconductor adsorbents or filtration materials. Mixing materials A and B may be straightforward, but separating them may require two to three times more effort. Expanding semiconductor production to meet SDGs without considering recycling and circular economy practices may lead to an increase in electronic waste, and such scenarios are currently unfolding. This poses challenges to the objectives of SDG 12 (Responsible Consumption and Production). It underscores the necessity for future research on semiconductor waste recycling.

4.3. Academic-industrial collaboration

Based on the results, it is evident that there is a significant gap in collaboration between the academic and industrial sectors. The results from the top 50 academic-industrial collaborations indicate that only a few large enterprises actively engage in such partnerships. Some small and medium-sized enterprises may be constrained by various interests, including financial considerations, technology outcomes, patent considerations, and ownership issues, which reduce opportunities for collaboration between academia and industry. This suggests that there is still a gap in promoting joint efforts by semiconductor companies to advance the SDGs. Therefore, it is essential for government authorities to play a joint role in facilitating collaboration between academia, industry, and the public sector. This would involve matchmaking enterprises, establishing long-term partnerships, and jointly nurturing talent. These actions are necessary to achieve the broader SDGs and will help bridge the gap between research and practical implementation within the semiconductor industry.

5. Conclusions

This study examined SDG-related semiconductor research from 2017 to 2022, with the literature showing linear growth in the total number of publications. Semiconductors, which can be found in almost every subject area (SDG 7, SDG 9, SDG 3, SDG 6, and SDG 13), are one of the materials representing a key technology. More specifically, scientists have been working on SDG 7-related green energy efficiency strategies with $>$11,000 publications per year since 2018, suggesting that semiconductors continue to promote the SDGs. The analysis also showed that SDG 7-related academic research accounts for 97.1 %, while research-industry cooperation's account for only 2.9 %; thus, the greatest contributor to SDG 7-related research is still academia. Some larger semiconductor companies have begun to incorporate SDGs into their strategies and business models, promoting ways to reduce carbon emissions and promote sustainable consumption. They have even started to associate SDGs with their business goals and KPIs to achieve substantial progress towards sustainable development goals. However, some companies may not be aware of the importance of SDGs, or may not have been properly guided to incorporate SDGs into their business strategies, leading to the problem of non-actual implementation of sustainable development. This may also be one of the factors contributing to the decline in industry-academic cooperation. As such, companies should be encouraged to establish partnerships with academia.

Author contribution statement

Shuchen Hsieh: Conceptualization, Funding acquisition, Writing - review & editing, Project administration, Supervision. Pei-Ying Lin: Methodology, Data curation, Formal analysis, Writing - original draft. I-Hui Lin, Ching-Hui Lin: Methodology, Data curation, Formal analysis. David E. Beck: Writing-review & editing.

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Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e21306.

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