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Review

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An intellectual property analysis: advances and commercialization of low-dimensional carbon materials in batteries

Chang Su[1], Xuan Gao[2,*], Kejiang Liu[3], Shudi Wang[4], Yuhang Dai[2], Haobo Dong[5], Yiyang Liu[2], Jiayan Zhu[4], Qiuxia Zhang[4], Guanjie He[2,*]

[1]Department of Management, Technology, and Economics, ETH Zürich, Zürich 8092, Switzerland.
[2]Christopher Ingold Laboratory, Department of Chemistry, University College London, London WC1H0AJ, UK.
[3]Department of Physics, Hong Kong Baptist University, Hong Kong 999077, China.
[4]State Key Lab of Superhard Materials, College of Physics, Jilin University, Changchun 130012, Jilin, China.
[5]Electrochemical Innovation Lab, Department of Chemical Engineering, University College London, London WC1E7JE, UK.

[*]**Correspondence to:** Dr. Xuan Gao, Dr. Guanjie He, Christopher Ingold Laboratory, Department of Chemistry, University College London, 20 Gordon St., London WC1H 0AJ, UK. E-mail: uccaxga@ucl.ac.uk; g.he@ucl.ac.uk

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Abstract

There is a growing demand for energy consumption in society due to the increasing application of emerging technologies. Therefore, the need for the development of advanced energy storage technologies to cope with the rising energy demand is rising. Carbon materials play significant roles in energy storage technologies. In this review, the research progress and applications of low-dimensional carbon materials in batteries, including carbon quantum dots, carbon nanotubes, and graphene, are summarized. The performance of these materials is compared against traditional lithium-ion batteries with graphite, which has limitations in its bandgap and reversible capacity. A mini-intellectual property analysis and the advances and commercialization of low-dimensional carbon materials in batteries were provided. The challenges and limitations associated with using these materials as electrode materials were discussed, and a market overview of their commercialization was provided. Finally, future directions for research and development in this field were concluded. Overall, this review provides a comprehensive overview of low-dimensional carbon materials as a promising research area for developing advanced batteries to meet the growing demand for energy consumption.

Keywords: Low-dimensional materials, carbon, battery, commercialization, binder, energy storage

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INTRODUCTION

As emerging technologies such as machine learning and artificial intelligence generated content are increasingly applied to human life, the demand for energy consumption continues to increase[1-3]. To cope with the increasing energy demand, the energy storage technology market continue to show hot investment enthusiasm during 2022-2023. Modern society has become increasingly reliant on batteries, demanding them to be smaller, lighter, have higher capacity, charge faster, safer, and last longer[4-6]. This is partly due to the global commitment to reducing reliance on traditional fuel sources, including oil, natural gases, and coal[7-9]. Another reason is their ubiquitous presence and necessity in our daily lives, from simple consumer electronics to being in every automobile in the near future[10]. However, the current widespread use of lithium-ion batteries (LIBs) with graphite anodes fails to keep up with energy demands[11]. The primary challenges associated with traditional batteries stem from their bandgap and reversible capacity. A larger bandgap implies a reduced likelihood of electron transition to the conduction band, consequently leading to an increased self-discharge rate. Moreover, the mitigation of electron migration within the cell prolongs the ability of batteries to maintain a charged state over an extended duration[12-15]. The materials used, primarily lithium, cobalt, and oxygen, exhibit overlapping or partially overlapping energy bandgaps between their electronic energy levels. This implies that electrons may move uncontrollably within the material, reducing the energy storage capacity, particularly in the positive electrode material, and consequently limiting the battery capacity[16]. Also, throughout the charging and discharging process, the change in the shape of electrodes and the buildup of a solid electrolyte interface (SEI) layer further decreases its capacity. Lastly, LIBs suffer greatly from volume expansion[17].

As such, one promising research area addressing this issue is low-dimensional carbon and development of novel batteries[18]. In general, carbon is a desirable material in various battery types due to its abundance, which leads to reduced costs, environmental friendliness, and chemical stability. Low-dimensional carbon, including the family of carbon materials, has been processed into nanomaterials and is classified based on its size in each spatial dimension[19-21]. These include carbon quantum dots (CQDs), carbon nanotubes (CNTs), and graphene nanosheets [Figure 1][22]. Nano-materialization, in general, greatly benefits material performance in batteries due to increased surface-to-volume ratios, surface effects, and other properties compared to regular materials[23]. Carbon nanomaterials also have the added benefit of high electrical conductivity, tunable structure, large surface area, and high porosity[24]. Companies, including Tesla, are actively exploring integrating these materials into electric vehicle batteries to extend driving ranges and reduce charging times. The increasing demand for high-performance, environmentally-friendly batteries aligns with the advancements in low-dimensional carbon materials, driving innovation in energy storage technologies.

The first recorded instance of a low-dimensional carbon material was in 1952 by Russian scientists Radushkevich and Lukyanovich, who created multi-walled CNTs with a diameter of 50 nm[25]. In 1991, Dr. Sumio IIjima discovered the single-walled CNTs, which sparked intense interest in the field throughout the scientific community[26]. Since then, many types of low-dimensional carbon materials have been employed in batteries to various degrees of success. The performance will be compared against the standard LIB with graphite. One-dimensional (1D) carbon materials have been used in cathode materials to improve the performance of lithium-sulfur (Li-S) batteries, which already have a much higher energy density[27]. They were chosen due to their high surface area, conductivity, flexibility, and stability. Similar findings were reported when single- and multi-walled CNTs were combined with other active materials to obtain higher specific capacities and current densities.

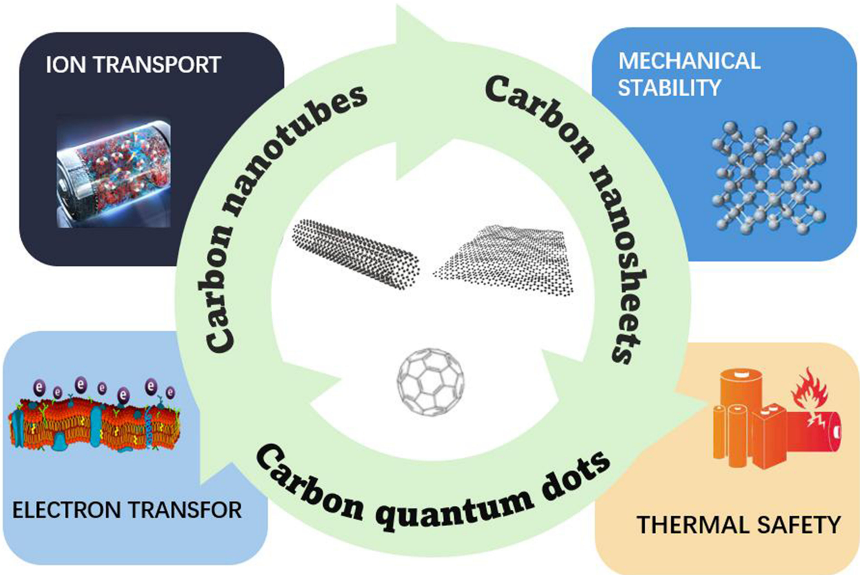

Figure 1. Carbon quantum dots, carbon nanotubes and carbon nanosheets and main properties of these low-dimensional carbon materials.

Low-dimensional carbon materials also find significant applications in the electrode materials of vanadium-based batteries. Vanadium-based materials, such as vanadium oxides [e.g., V_2O_5, V_6O_{13}, $V_3O_7{\cdot}H_2O$@C, VO_2 (B), V_2O_3] and vanadates (e.g., Li_3VO_4, $NaVO_2$, NaV_2O_5), are commonly employed as electrode materials in LIBs, zinc batteries, and sodium batteries due to their high specific capacity, abundant resources, and low cost. The emergence of low-dimensional materials further advances the performance of these electrode materials. Carbon materials serve as conductive additives in the positive electrode materials, and layered or wire-like carbon structures facilitate ion transportation and electron transfer. However, challenges such as severe internal aggregation and pulverization persist with these nanoscale carbon materials, exacerbated by their large surface area leading to low tap density. Currently, constructing hierarchical porous structures shows promising prospects for addressing these issues. Porous structures inherit the advantages of nanoscale building blocks while enhancing the electrode material's specific surface area and mechanical stability, facilitating ion insertion/extraction (e.g., Li^+, Zn^{2+}/Na^+). Additionally, fabricating free-standing electrodes presents an effective approach to mitigate the self-aggregation of nanomaterials. Gao *et al.* proposed a facile *in-situ* engraving method on copper foil to prepare highly dispersed and orderly porous structures, providing sufficient open space and rapid electron transport pathways to address nanomaterial aggregation effectively[22].

This paper presents an intellectual property analysis of the advances and commercialization of low-dimensional carbon materials in batteries. We review the research progress of these applications. Detailed global patent analysis is discussed, and directions for commercialization are given. We also discuss the challenges and limitations associated with their use as electrode materials and provide a market overview of the commercialization of these materials. Finally, we outline future directions for research and development in this field.

APPLICATION OF LOW-DIMENSIONAL CARBON MATERIALS IN BATTERIES

Low-dimensional carbon materials

The excellent performance of carbon materials stems from the controllable assembly of carbon building blocks, enabling versatile structural configurations. Different dimensions [zero-dimensional (0D) points, 1D linear or tubular structures, two-dimensional (2D) planes, and three-dimensional (3D) network structures] directly influence properties such as specific surface area, pore structure, thermal stability, and mechanical stability of carbon materials, which are deeply interconnected with their controllable structures and dimensions[28]. Particularly in electrodes, the cooperative interaction between high-energy-density active materials (such as manganese, vanadium, and lithium metal oxides) and low-dimensional carbon materials holds promise for enhancing the electrochemical performance of batteries. Currently, layered structures are commonly employed in low-dimensional carbon materials, where each layer exhibits relatively weak interlayer interactions but strong in-plane covalent bonding. However, nanosheet-like carbon materials are prone to aggregation or overlapping during electrode material compositing, resulting in limited specific surface area and ion diffusion efficiency. Porous channels offer a solution to this issue by perforating graphene nanosheets, providing high-speed pathways for ion diffusion and increased surface area for chemical reactions. Figure 2A illustrates an efficient 3D conductive network architecture achieved by *in-situ* anchoring of CNTs between graphene layers, while Figure 2B and C demonstrates the improved adhesion between graphene layers upon the inclusion of CNTs, showcasing broad ion transport channels and electron transfer pathways. Correspondingly, chemical modification serves as a controllable means to enhance the performance of carbon materials units. Currently, extensive research has been conducted on atomic doping and incorporation of metal ions or polymers for intercalation, among other methods, to further adjust band gap, conductivity, and thermal stability. In order to maximize the unfolding of carbon nanosheets, various chemical modifications are explored.

Maximizing the interlayer spacing between nanosheets also aids in adjusting their band gap and Fermi level, thereby enhancing their conductivity and ion diffusion efficiency. It also facilitates the intercalation of metal ions or polymers, ensuring the establishment of a conductive network architecture and the presence of sufficiently large channels to facilitate ion transport. Typically, 2D graphene nanosheets and 1D CNTs can be assembled into 3D conductive network structures. The establishment of such 3D structures will be beneficial for improving interfacial reaction kinetics and ensuring that electrochemical activity remains active.

Anode materials

An anode material plays a crucial role in the battery performance. It is responsible for storing and releasing lithium ions during the charge and discharge process in LIBs. The anode material should have high capacity, good conductivity, and stability to ensure efficient and safe battery operation. Historically, Graphite, $Li_4Ti_5O_{12}$, silicon, and lithium metal are among the commonly chosen anode materials for lithium batteries. Graphite, due to its outstanding stability and electrochemical performance, has emerged as the most commonly used negative electrode material. However, as the demand for high-energy-density batteries increases, its limitations become apparent, and alternative anode materials, including low-dimensional carbon materials, are gaining attention. Low-dimensional carbon materials, such as CNTs, graphene, and CQDs, have attracted significant attention in recent years as anode materials for LIBs due to their unique structural and electronic properties. These materials possess high specific surface area, excellent electrical conductivity, and high mechanical strength, making them promising candidates for next-generation batteries. Low-dimensional carbon materials also have a high lithium-ion storage capacity and can withstand repeated charge-discharge cycles, resulting in long battery life. In addition, the unique properties of these materials allow for the design of new electrode architectures and the incorporation of other materials, such as metal oxides and sulfides, to enhance their electrochemical properties.

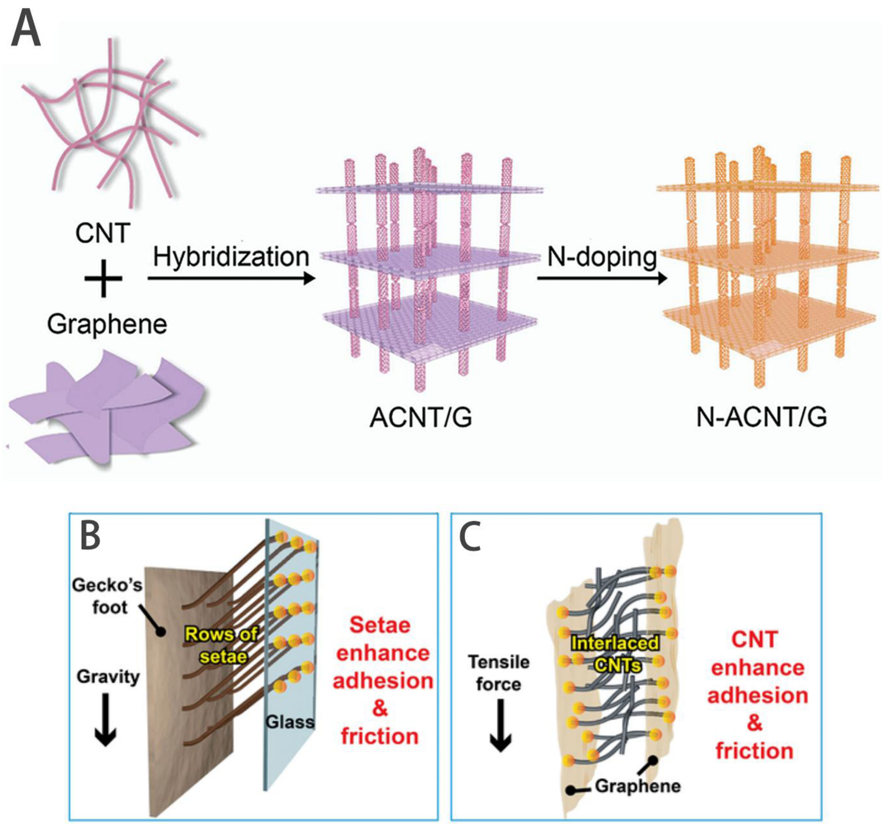

Figure 2. (A) A schematic design illustrating the construction of a three-dimensional conductive network architecture using two-dimensional graphene nanosheets and one-dimensional carbon nanotubes; (B and C) Introduction of carbon nanotubes to enhance the adhesion between graphene layers. Copyright 2021, Wiley-VCH. CNT: Carbon nanotube.

CQDs are small carbon nanoparticles with sizes below 10 nm. They possess unique electronic properties, such as high surface area and good conductivity, making them potential candidates for use in energy storage devices. As an anode material, they have demonstrated high specific capacity, good rate capability, and excellent cycling stability. CQDs have also been incorporated into composites with other materials, such as metal oxides, to further enhance their electrochemical properties. Recent studies have shown that their surface functionalization can improve their electrochemical performance. As another 0D carbon material, nanodiamonds have also received attention in recent years. Gao *et al*. introduced them into TiO_2-based anodes to enhance their specific capacity[29]. CNTs have been used as anode materials in various battery systems, including LIBs, sodium-ion batteries (NIBs), and potassium-ion batteries (KIBs). Recent studies have shown that functionalized CNTs can further enhance their electrochemical performances. Graphene is a 2D sheet of carbon atoms arranged in a honeycomb lattice and has excellent electrical conductivity, high specific surface area, and high mechanical strength, making it a promising material for use in LIBs. As an anode material, it exhibits high lithium-ion storage capacity, good rate capability, and excellent cycling stability. It has also been incorporated into composites with other materials, such as metal oxides and sulfides, to improve its electrochemical properties. However, graphene is prone to restacking, which limits its specific surface area and affects its performance.

As research progresses, alloy-type anode electrode materials [such as Aluminum (Al), Tin (Sn), Magnesium (Mg), Silver (Ag), Antimony (Sb), and their alloys], some conversion-type transition metal compounds, silicon, and silicon-based compounds will be applied in the development of positive electrode materials.

However, the application of these materials inevitably comes with certain drawbacks. For instance, silicon anodes undergo significant volume changes during ion insertion or extraction, which poses considerable challenges to the mechanical stability of batteries. Additionally, it leads to instability of the SEI layer, poor contact between the active material and the current collector, material pulverization, and other issues. Furthermore, some materials exhibit poor conductivity, high processing costs, or scarcity of raw materials, presenting challenges. In contrast, as a commercially established anode material for lithium batteries, graphite has a relatively mature system, stable mechanical structure, and electrochemical performance. Moreover, low-dimensional carbon materials offer superior ion transport and electron transfer capabilities compared to traditional graphite electrodes, along with a larger specific surface area, rendering them highly promising for further research endeavors.

Cathode materials

Low-dimensional carbon materials are also being widely studied as cathode materials for batteries due to their unique properties, such as high conductivity, large surface area, and good stability. These properties make them suitable for use in cathodes for various types of batteries. Afyon *et al*. hacous nanospheres using the ultrasonic nebulized spray pyrolysis technique, subsequently transformed into nano h-$LiMnBO_3$ with an average crystallite size of 14 nm, embedded within a conductive matrix comprising reduced graphite oxide and amorphous carbon to form a composite electrode. This composite demonstrated a discharge capacity of 110 mAh/g at a C/15 rate within the 4.5-2V range, exhibiting relatively stable cycling with a discharge capacity loss of approximately 0.9% over the first 50 cycles, indicating a reduction in the polarization degree. The small particle size of h-$LiMnBO_3$ and its dense arrangement within the conductive network are credited with enhancing the electrochemical performance. Subsequent strategies involving particle size reduction, conductive network formation, and metal site doping are anticipated to further improve cycling stability, thereby paving new avenues for research into cathode materials for lithium batteries[30]. One of the most widely studied low-dimensional carbon materials for use as a cathode in batteries is graphene. Graphene has a high surface area and excellent conductivity, which allows for fast and efficient charge transfer. In addition, its unique 2-D structure provides a large number of active sites for electrochemical reactions to occur, leading to high capacity and excellent cycling stability. Graphene can be functionalized with various functional groups, which can improve its electrochemical properties further. In an aqueous energy storage system, H^+ is a factor that researchers should consider. Xu *et al*. studied charge storage mechanism of reduced graphene oxides (rGO) in aqueous zinc energy storage devices in 2022[31]. H^+ interacts more strongly with graphitic domain carbon atoms than Zn^{2+}, according to structural energy depicted in Figure 3A. H^+ adsorption has reduced energy due to charge redistribution between H^+ and rGO nanosheets [Figure 3B]. Figure 3C illustrates the computed adsorption energies of H^+ and Zn^{2+}, while Figure 3D displays the optimized charge-density differences between H-rGO and Zn-rGO. The density of states (DOS) pattern of the optimized system confirms H-C orbital overlap, indicating the rupture of the graphitic domain's cloud and C sp^2-sp^3 re-hybridization [Figure 3E]. However, Zn^{2+} adsorption hardly influences C orbital [Figure 3F].

CNTs are another low-dimensional carbon material being studied as a cathode material in batteries. They have a high surface area and high conductivity, which allows for fast and efficient charge transfer[31]. In addition, they have excellent mechanical and thermal stability, making them suitable for use in high-performance batteries[32]. CNTs can also be functionalized with various functional groups to improve their electrochemical properties. CQDs are another promising low-dimensional carbon material for use in battery cathodes. They have a unique quantum confinement effect, making them suitable for enhancing battery conductivity and activity. They also have a high surface area and good conductivity, which allows for efficient charge transfer. Furthermore, CQDs can be synthesized in various sizes and shapes, which can be tuned to further improve their electrochemical properties.

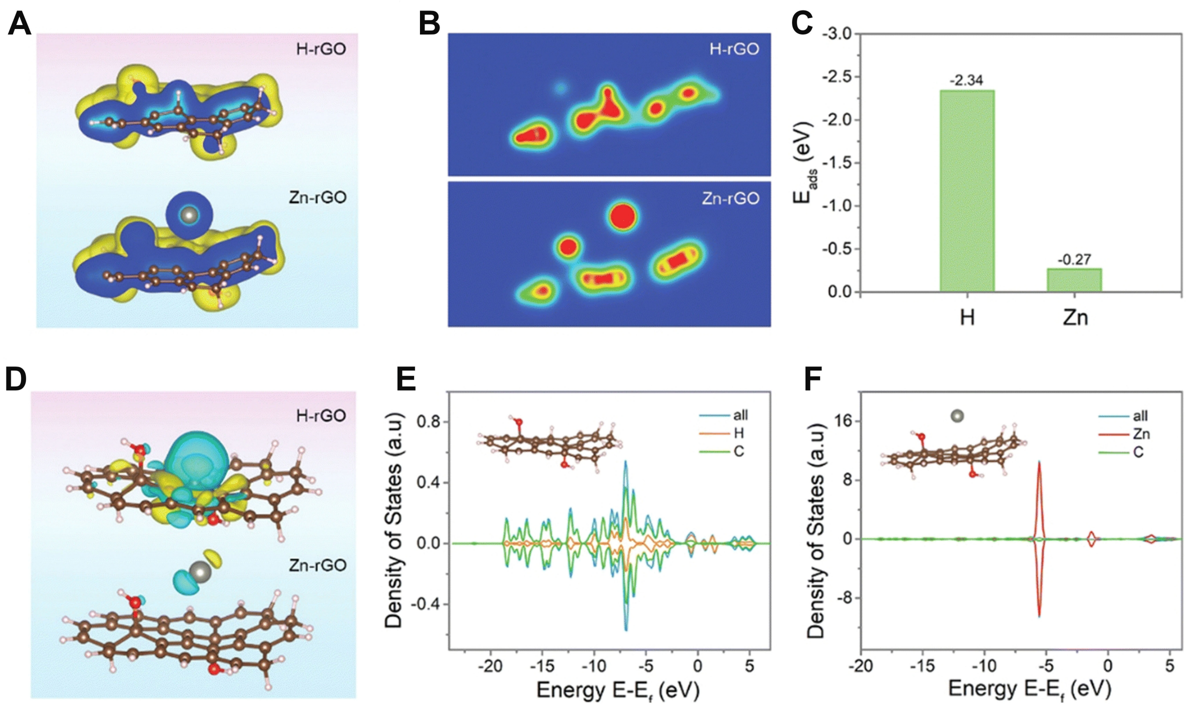

Figure 3. The calculated properties of rGO with the H^+ and Zn^{2+} adsorption. (A) Structural energy; (B) charge distribution; (C) adsorption energy; (D) optimized charge density difference; and DOS of rGO with the (E) H^+ and (F) Zn^{2+} adsorption[28]. Reused with permission from Wiley. rGO: Reduced graphene oxide; DOS: density of states.

Other low-dimensional carbon materials being studied for use as cathode materials in batteries include carbon fibers, nanospheres, and nanowires. These materials have unique properties that make them suitable for use in batteries, such as high surface area, good conductivity, and high stability.

Conductive agent

Conductive agents play a critical role in facilitating the electron transport within the electrode materials of batteries, thereby improving their electrochemical performances. Carbon black can no longer meet the technological progress of high loading, high specific surface area, efficient charge transfer network, and simple mixing. Low-dimensional carbon materials are introduced as conductive agents to solve this problem. CNTs have been widely used as conductive agents in LIBs due to their high electrical conductivity and large surface area. Table 1 presents the electrochemical performance of lithium batteries with different conductive additives, including CNTs, vapor-grown carbon fibers, acetylene black, and flake natural graphite, as measured by discharge specific capacities at various rates. The superior structure and properties of CNTs lead to lithium batteries augmented with them as additive materials exhibiting enhanced and sustained electrochemical performance. In 2022, Gao *et al*. introduced CNTs into manganese oxide to prompt the interfacial transfer pathway of zinc ions in zinc-ion batteries (ZIBs), resulting in a significant improvement in its electrochemical performance, including higher discharge capacity, better rate capability, and improved cycling stability[33]. As shown in Figure 4A, Zn^{2+} can only move in narrow channels of pure manganese oxide, reducing its migration rate and hindering battery long-cycling stability. Instead, the interface formed between the manganese oxide and CNTs [Figure 4B], allows Zn^{2+} to flow smoothly in the cathodes. In Figure 4C, several transferred electrons show that the Mn-O-C link considerably affects the chemical environment of Mn ions. Similarly, the addition of CNTs to the anode material of LIBs resulted in a higher discharge capacity and better cycling stability.

Table 1. Electric performance of different conductive agents in lithium-ion battery

Material	CNT	VCF	AB	FNG
Specific capacity (0.5 C)	125 mAh/g	118 mAh/g	101 mAh/g	116 mAh/g
Specific capacity (1 C)	122 mAh/g	103 mAh/g	100 mAh/g	114 mAh/g
Specific capacity (2 C)	120 mAh/g	101 mAh/g	87 mAh/g	102 mAh/g
Specific capacity (3 C)	109 mAh/g	94 mAh/g	76 mAh/g	98 mAh/g

CNT: Carbon nanotubes; VCF: vapor-grown carbon fibers; AB: acetylene black; FNG: flake natural graphite.

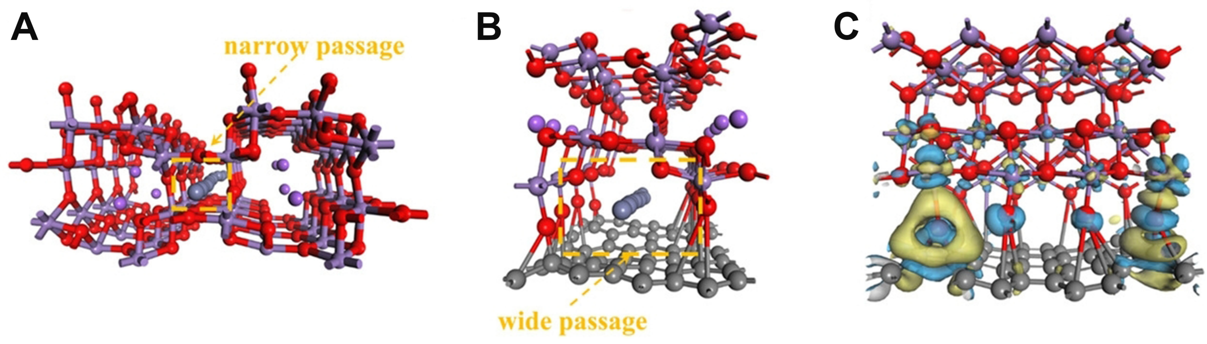

Figure 4. Schematic depiction showing zinc ion migration in (A) bulk manganese oxide; (B) at the manganese oxide CNT interface; and (C) the charge density differential at the interface[1]. Reused with permission from Wiley. CNT: Carbon nanotube.

Graphene is another low-dimensional carbon material that has been extensively investigated as a conductive agent or an active material in batteries. Graphene oxide (GO) was used as a conductive agent in a Li-S battery, resulting in improved electrochemical performance, including higher specific capacity, better rate capability, and improved cycling stability. In a recent scientific publication, Xu *et al*. have provided a detailed account of their remarkable findings. Their research highlights a fascinating discovery involving using a nanoscale-thick layer of GO, which was skillfully coated onto the surface of a CNT film, ensuring an even distribution. By implementing this ingenious interlayer technique, substantial advancements in the efficiency of Li-S batteries have been successfully demonstrated. The outcomes demonstrate that the porous GO/CNT film plays a crucial role in enabling the electrolyte to penetrate and promoting the transport of ions. Moreover, it effectively mitigates the volume expansion of cathodes during charging and discharging. Furthermore, by incorporating trace amounts of GO, the cycling stability of cells is significantly enhanced. Consequently, the battery maintained a consistent ability to hold and release energy at around 600 $mAh \cdot g^{-1}$ during a span of 300 cycles. This achievement was accomplished by employing a loading density of 25 $\mu g \cdot cm^{-2}$ on the CNT film[34].

COMMERCIALIZATION OF LOW-DIMENSIONAL CARBON MATERIALS IN BATTERIES

Patent analysis is the process of analyzing and evaluating patents to gather insights into a particular technology, market, or industry and involves reviewing patent documents to understand the scope and nature of the invention, its potential applications, and its potential impact on the market[35]. It is an important tool for companies to gain insights into the competitive landscape, identify potential research and development opportunities, evaluate potential acquisitions, and assess patentability and freedom to operate.

Low-dimensional carbon materials, such as graphene and CNTs, possess unique properties not found in bulk carbon materials, and they have various potential applications in fields such as electronics, energy, and biotechnology[36]. These materials are relatively easy to produce in large quantities, and their interdisciplinary nature makes them an attractive research topic for collaboration and exploring new areas. In short, their valuable properties, potential applications, scalability, and interdisciplinary nature in patent analysis make them an important research focus[37].

Based on the patent database of the China Knowledge Center for Engineering Sciences and Technology (CKCEST), this study conducts searches with keywords, data cleaning and professional analysis for patents about low dimensional carbon material technology, analyzing the development history, technology hotspots, evolutionary trends, network among countries, institutions and researchers for inferring the trend of this technology. In total, 4,080 records related to patents regarding low-dimensional carbon materials were retrieved from the CKCEST by 2023, with an overall increasing trend, and the number increased more significantly in 1994, 1995, 1999, and 2000, and peaked at 445 in 2003.

Patent analysis

The trend of the number of patents could, to a certain extent, reflect the development status, hotness and trend of a certain technology category or research field[38]. Statistics on the number of patents and its growth rate for this technology topic over the years, alongside the number of patents and its cumulative number [Figure 5]. The total number of patents for low-dimensional carbon material is 4,080, with an overall increasing trend. Specifically, the number in this field increased more significantly in 1994, 1995, 1999 and 2000, with a peak of 445 patents in 2003.

The concept of technology life cycle originates from the product life cycle, and the key points of technology life cycle theory are based on the perspective of technology itself, compared with the perspective focusing on products and markets[39]. The technology life cycle is broken down into two dimensions, including competitive impact and product and manufacturing integration, and four stages, including embryonic, growth, maturity and recession stages. In addition to measuring the development trend of a single technology over time, the technology life cycle theory can also be used to evaluate the change in the existing market for similar technologies or the performance of the technology [Figure 6A]. The technology life cycle is drawn according to the changes in the number of patents and applicants over the years to determine the stage of the low-dimensional carbon material. Comparing it with the standard curve, it is known that low-dimensional carbon material is currently in the growth stage.

The theme mapping draws on the contour map in Geographic Information System (GIS) to visualize the technology theme data, distinguishing the amount of thematic data and the relationship between thematic data by the shades of color[40]. The theme mapping is one of the typical metrological methods for conducting thematic layout analysis for a specific technology. In particular, each node represents a technical theme, and the distance between two words is positively related to the strength of the relationship between them. In addition, peak area in the center of the contour line indicates a technical theme cluster. The theme mapping is plotted as shown in Figure 6B, which shows the main theme mapping clusters including CNTs, nanotechnology, and composite materials for patents about low-dimensional carbon materials. Moreover, low-dimensional carbon materials are also being used in medicine due to their different functions, such as drug delivery and biosensors.

Theme evolution analysis, as one of the emerging trend exploration methods, assists in understanding the process of theme generation, extinction, enhancement, weakening, aggregation and fission, which is widely used in patent analysis and has also received the attention of many researchers[41]. Before 2000, the main themes were CNTs, composite materials and metal fibers. From 2001 to 2005, the focus shifted to CNTs, animals, mice, obesity, leptin, DNA-binding proteins and trans-activators. The theme evolution trends from

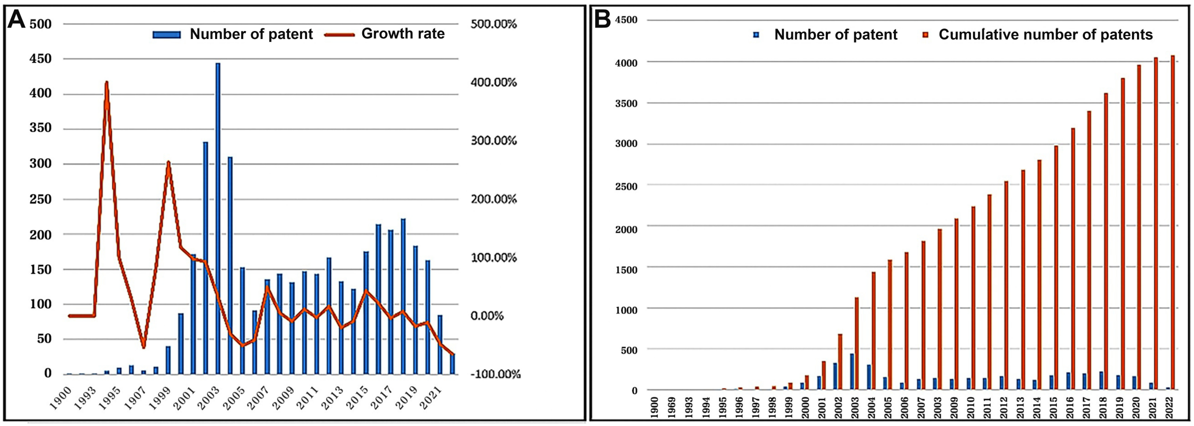

Figure 5. (A) Low-dimensional carbon material patent volume and growth rate and (B) low-dimensional carbon material patent volume and cumulative number.

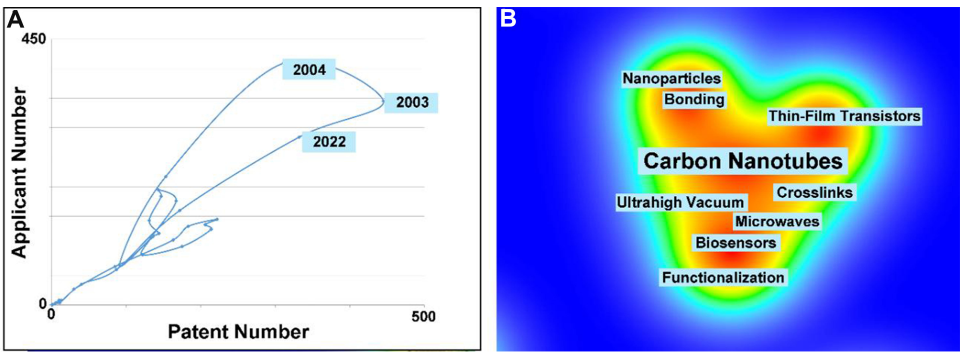

Figure 6. (A) Low-dimensional carbon material technology life cycle analysis and (B) theme mapping.

2005 to 2013 have the largest change [Figure 7A]. From 2006 to 2010, primary themes comprised biosensors, CNTs, electrochemistry, functionalization, porous membranes, colon cancer, min mouse, proteomics, and differential mass spectrometry. In 2013, the emphasis turned to CNTs, thin-film transistors, *etc*. From 2013 to 2023, the prominent themes included CNTs, nanotube separation, thin-film transistors, and display electronics. The analysis reveals that the application scenarios of low-dimensional carbon materials are gradually diversifying, from basic material processing to medical-related solutions to complex technological devices.

Applicant network analysis is a patent analysis method that involves identifying the strength of relationships between the various patent applicants[42]. In particular, the size of the nodes in Figure 7B is proportional to the number of patents, and the red, green and yellow nodes indicate the number of patents with the first, second, third and later applicants, respectively. The thickness of the connecting lines is proportional to the number of co-authored patents. Through the analysis, two closely cooperating groups are found. Specifically, it is evident that William Marsh Rice University, James Mitchell Tour, Carbon Nanotechnologies Corporation, and Georgia Tech Research Corporations constitute the largest cooperative group in this field. Hon Hai Precision Industry Company and Tsinghua University have formed a cooperative commercialized partnership in China. There are not many cooperation relationships among the applicants in the field of low-dimensional carbon materials, and most of them applied for patents independently. This indicates the importance of strengthening collaborative commercialization process in this field.

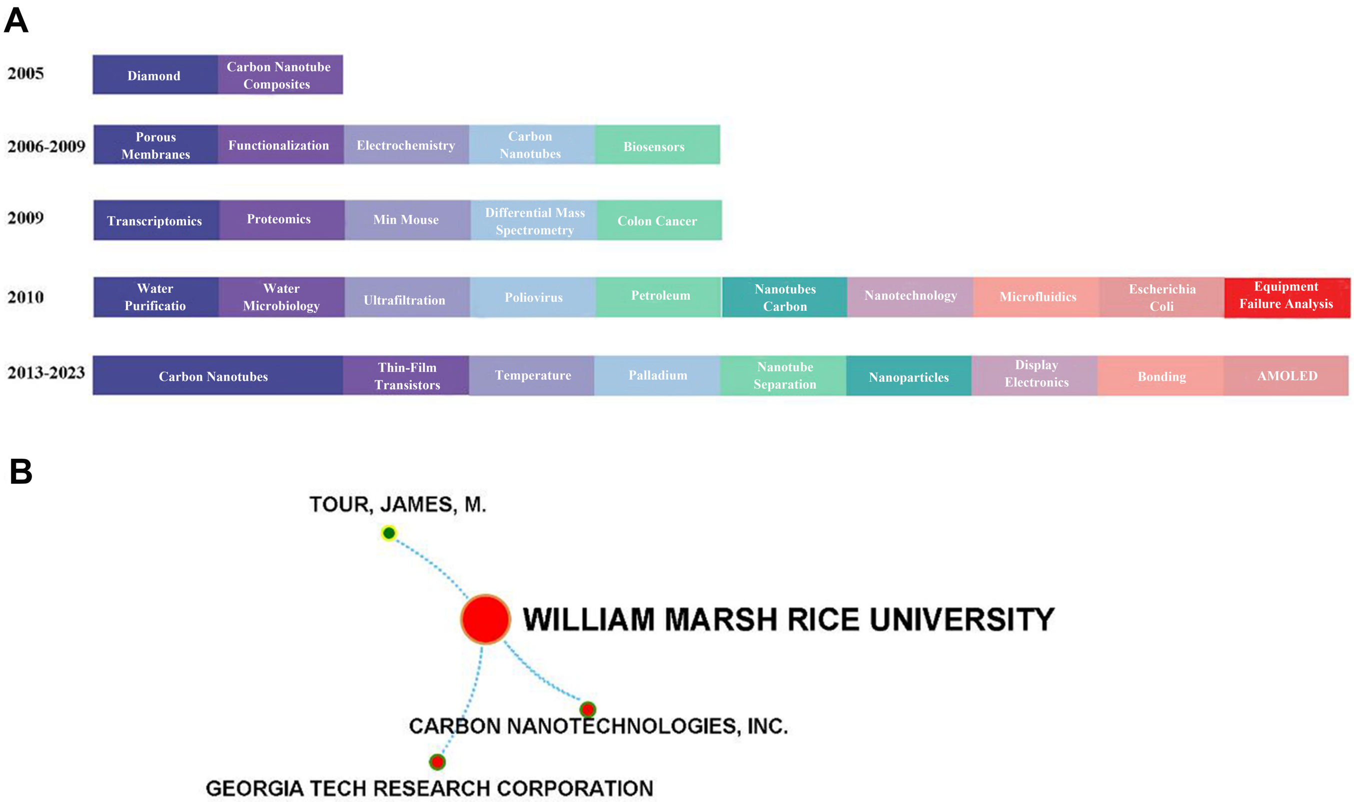

Figure 7. Low-dimensional carbon material (A) theme evolution analysis from 2005 to 2023 and (B) applicant network analysis.

At present, academic and corporate entities within China and the United States dominate the landscape of patent applications. Table 2 delineates the essential characteristics of leading applicants in low-dimensional carbon materials, encompassing their respective affiliations, the volume of patents filed, their relative percentages, and geographical affiliations.

Current market status

The use of low-dimensional carbon materials in batteries has been extensively researched in the past few decades. These materials have shown great potential in enhancing the battery performance, including increasing the energy and power densities, improving the cycling stability, and reducing the manufacturing cost. As a result, the market for these materials in batteries has been growing rapidly. Currently, several low-dimensional carbon materials have been commercialized for use in batteries. For example, graphene-based anode materials have been used in commercial LIBs, and CNTs have been employed as conductive agents in various battery systems. Additionally, CQDs have also shown promise as anode and cathode materials.

The global market for low-dimensional carbon materials in batteries was valued at around $335 million in 2020, and it is expected to reach $1.5 billion by 2028, growing at a compound annual growth rate of around 20%. The increasing demand for electric vehicles, portable electronic devices, and renewable energy storage systems is driving the growth of the market. In terms of geography, Asia-Pacific is the largest market, accounting for more than half of the global market share. This is due to the increasing production of LIBs in countries such as China, Japan, and South Korea and the growing demand for electric vehicles and renewable energy storage systems in the region. The market is highly competitive, with several key players operating in the industry. These include companies such as Showa Denko K.K., Cabot Corporation, Arkema S.A., and Nanocyl S.A., among others. Samsung is also one of the major companies involved in the

Table 2. Main applicant patent number

No.	Applicant	Number	Percentage	Country/Regions
1	William Marsh Rice University	143	3.505%	USA [99.296%]
2	International Business Machines Corporation	74	1.814%	USA [85.897%]
3	Hon Hai Precision Industry Co., Ltd.	71	1.740%	China [100.000%]
4	Lg Chem, Ltd.	68	1.667%	Korea [97.143%]
5	Tsinghua University	46	1.127%	China [100.000%]
6	The Regents of the University of California	29	0.711%	USA [96.552%]
7	Hyperion Catalysis International, Inc.	28	0.686%	USA [100.000%]
8	Lockheed Martin Corporation	24	0.588%	USA [100.000%]
9	The Board of Regents of the University of Oklahoma	22	0.539%	USA [90.909%]
10	Intel Corporation	22	0.539%	USA [100.000%]
11	Hon Hai Precision Industry Co.	22	0.539%	China, Taiwan [90.909%]
12	NEC Corporation	21	0.515%	Japan [100.000%]
13	Molecular Rebar Design, LLC	21	0.515%	USA [80.769%]
14	Nanocomp Technologies, Inc.	21	0.515%	USA [100.000%]
15	Industrial Technology Research Institute	21	0.515%	China, Taiwan [86.364%]
16	Shou-Shan Fan	20	0.490%	China [95.000%]
17	Wisconsin Alumni Research Foundation	20	0.490%	USA [100.000%]
18	Tour, James, M.	20	0.490%	USA [100.000%]
19	Carbon Nanotechnologies, Inc.	19	0.466%	USA [100.000%]
20	Georgia Tech Research Corporation	19	0.466%	USA [100.000%]

research of low-dimensional carbon materials. Currently, it has developed a valuable method for synthesizing single-crystal graphene chips, which holds the potential to facilitate large-scale production of monolayer graphene. These companies are investing in research and development to develop new and innovative low-dimensional carbon materials for use in batteries.

CONCLUSION AND OUTLOOK

The progress made in the application and commercialization of low-dimensional carbon materials in batteries has shown great promise. The advantages of using these materials as anode and cathode materials and conductive agents have been demonstrated through numerous studies. These materials have the potential to enhance the performance and durability of batteries, which are crucial for developing advanced energy storage systems that can support the increasing demand for portable electronic and electric vehicles.

However, challenges and limitations still need to be addressed before low-dimensional carbon materials can be widely adopted in commercial batteries. One of the main challenges is the scalability and reproducibility of the synthesis of these materials. Many current synthesis methods are not scalable, and the production cost can be high. Chemical vapor deposition (CVD) is a highly effective chemical technique for preparing monolayer graphene materials. It involves heating a gas mixture (containing at least one carbon-containing gas) and precisely controlling the gas and liquid ratio on a substrate (copper or nickel) to form graphene layers, which are then heated in a vacuum to form monolayer graphene chips. However, once this method is applied industrially, macroscopic changes in the system can lead to significant variations in the microscopic environment. Changes in the angle of gas flow direction can result in significant thickness and size changes of graphene films. Additionally, high-temperature processes typically result in slow growth rates, and achieving high temperatures and vacuum environments on a macroscopic scale is challenging and costly. This presents a trade-off between production quality and yield. Currently, high-quality graphene films can be obtained by epitaxial growth of graphene on the SiC surface, exhibiting uniform crystal orientation and excellent monolayer controllability, while also suppressing ripple formation on the chips. However, the high cost and performance and challenges related to graphene transfer and SiC reuse remain among the key challenges to be addressed. In addition, the performance and durability of low-dimensional carbon materials in batteries can be affected by factors such as impurities, defects, and structural stability. Addressing these issues will require further research and development efforts.

Another important consideration for commercializing low-dimensional carbon materials in batteries is their environmental impact and recycling. As with any new technology, their potential environmental impact needs to be carefully evaluated. In addition, their recycling needs to be considered to minimize waste and maximize the sustainability of the battery industry.

Despite these challenges and limitations, the potential benefits of using low-dimensional carbon materials in batteries make them a promising area for further research and development. Future research directions could focus on improving the scalability and reproducibility of synthesis methods, enhancing the performance and durability of these materials, and evaluating their environmental impact and recycling. Additionally, research could explore the potential use of low-dimensional carbon materials in other energy storage systems, such as supercapacitors and fuel cells. The development of these materials for use in batteries is an exciting research area with enormous potential for enhancing the performance and sustainability of energy storage systems. Despite the challenges and limitations to overcome, the progress made to date suggests that continued research and development in this area is well worth pursuing.

Methodology of patent analysis

Patent analysis holds significant importance as it serves multiple pivotal purposes. It enables enterprises, research institutions, and governmental bodies to predict technological trends, assess innovative competitiveness, safeguard intellectual property rights, guide research and development investments, identify collaborative opportunities, and foster knowledge exchange. Thorough scrutiny of patent data empowers organizations to strategically plan, mitigate risks, and expand their market footprint, ultimately gaining a competitive edge in dynamic markets while concurrently promoting successful innovation and industry advancement.

As the annual number of patent applications continues to surge, effective data management becomes increasingly critical. Patent retrieval (PR) is vital for patent analysis, but it faces challenges different from general information retrieval. Automated PR needs improvement in recall rates. Collaboration with patent professionals is essential to develop interactive search tools. Advanced patent analysis tools are in demand for tasks such as forecasting technological trends and patent quality assessment. However, these tools have limitations, including potential accuracy issues with extensive patent data[43]. Future research should focus on refining algorithms and enhancing efficiency. Evidently, the successes achieved in information retrieval applications such as web search in recent years cannot be directly transposed into the PR field, demanding conscious domain adaptation and customization.

Additionally, Abbas *et al*. conducted an evaluation on the CLEF-IP 2010/2011 collection, exploring certain challenges, particularly when only partial patent applications are available for prior art searches, such as titles, abstracts, extended abstracts, or descriptions[44]. The article also points out that many data sources related to patents have not been fully explored in PR literature. These data sources could offer breakthrough improvements in PR, such as reexamination records, Patent Trial and Appeal Board (PTAB) decisions, differences between patent application and grant versions, examiner/applicant communications, and litigation history[45].

Additionally, Korobkin *et al*. have introduced an innovative method that combines statistical and semantic elements to improve the accuracy of prior art searches[46]. In the statistical analysis part, various techniques are used to statistically analyze patent documents, including term extraction, patent database storage, and patent comparisons. The effectiveness of these methods is evaluated using three different tokenization approaches: stop-word removal, synonym replacement, and N-gram tokenization[47].

In the semantic analysis section, they create a semantic tree to analyze patent applications and claims. However, it is worth noting that constructing and searching semantic trees requires more resources compared to statistical methods, especially when dealing with large patent collections. They also propose different variations of statistical analysis using the Latent Dirichlet Allocation (LDA) method. In the semantic analysis step, they employ a novel approach based on Stanford dependencies and the Meaning-Text Theory to build a semantic network. This technique calculates semantic similarity by comparing the semantic trees of patent applications and claims. In summary, to streamline prior art searches and handle extensive patent data more efficiently, researchers have developed an automated patent examination system[48].

Future research directions primarily include the following aspects: Firstly, there is a need for further development and enhancement of patent analysis tools and techniques to address the ever-increasing volume and complexity of patent documents; Secondly, research efforts should focus on strengthening text mining and natural language processing techniques for patent data to better extract and analyze patent information; Thirdly, advanced visualization techniques need further development to present patent analysis results in a graphical format, facilitating more intuitive comprehension and utilization of patent data. Additionally, research into deep learning and machine learning methods for patent analysis is essential to enhance accuracy and efficiency; Fourth, exploring interdisciplinary research at the intersection of patent analysis with other domains such as knowledge graphs and artificial intelligence is crucial to expanding the applications and value of patent analysis[49]; Fifth, addressing the issue of search scope: Prior art searches require comprehensive coverage of all previously published materials, whether patent or non-patent documents, in electronic or print forms. Achieving such comprehensive coverage is nearly impractical; Sixth, language-related challenges: Search processes must account for materials written in different languages; Seventh, the limitations of traditional information retrieval methods: Traditional information retrieval methods often exhibit suboptimal performance when confronted with prior art search tasks[50].

Although the research community is highly interested in PR, this field still faces numerous challenges and unresolved issues, necessitating interdisciplinary collaboration between the legal and computer science research communities to address them.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Su C, Gao X, Liu K
Performed data acquisition and provided administrative, technical, and material support: Wang S, Dai Y, Dong H, Liu Y, Zhu J, Zhang Q, He G
Manuscript proofreading and revision: He G

Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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