

Review

Recent Advances in Co-Occurrence Network of Super-Wetting Materials and Their Application in Agricultural Engineering: A Critical Review

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Abstract: Global food security is a critical issue, necessitating greater attention to the relationship between agricultural productivity and the ecological environment. Super-wetting materials, with their unique micro-rough structures and low surface energy, hold significant potential for addressing challenges in agricultural engineering. This review explores the research landscape of super-wetting materials by analyzing their temporal distribution, institutional and scholarly contributions, co-occurrence networks, and emerging keywords. These analyses reveal the research strengths, hotspot distributions, evolving concepts, and development trends in the field. Additionally, recent advances in the application of super-wetting materials in agricultural engineering—such as agricultural films, controlled-release fertilizers, and pesticide spraying—are highlighted. In the future, super-wetting materials and their research prospects in agricultural engineering are proposed in combination with the development trend, which provides support and inspiration for cultivating and developing new quality productive forces in agriculture and promoting sustainable agricultural development.

Keywords: super-wetting materials; agricultural engineering; ecological environment; co-occurrence network



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1. Introduction

Agriculture is essential for sustaining human society, providing food and nutrients, and maintaining ecological balance. However, recent global reports have highlighted the growing food insecurity crisis [1–5]. In July 2023, “The State of Food Security and Nutrition in the World” report by the FAO and other organizations revealed that 735 million people are now suffering from hunger due to various crises, with a significant portion facing severe food insecurity [6]. And “The 2024 Global Report on Food Crises” pointed out that, in 2023, about 281.6 million people in 59 countries and regions around the world faced serious food insecurity [7], as shown in Figure 1. According to the United Nations forecast, by 2050, the global population will reach 9.8 billion, and agricultural productivity will need to be increased by 70% to meet the growing demand [8–10].

Historically, the Green Revolution of the 1960s significantly boosted crop yields, but also led to negative environmental impacts like water pollution and soil degradation [11–14]. Given the unsustainable nature of traditional agricultural practices, there is an urgent need to balance high agricultural yields with ecological preservation [15,16]. This has made sustainable agriculture a cornerstone of global food security and a key objective of the United Nations’ Sustainable Development Goals [17].

Agricultural production growth primarily stems from increased inputs and technological advancements [18,19]. However, the “SOLAW 2021” reports by the United Nations

indicate that the Earth's soil, land, and water resources are deteriorating [20,21], suggesting that the sustainable development of agriculture in the future not only depends on the improvement of productivity, but also requires innovative technologies to cope with environmental and resource constraints [22–25]. As traditional agricultural practices face increasingly severe challenges, it is particularly important to find technologies that can increase agricultural output without increasing resource consumption. Super-wetting materials in materials science have begun to attract widespread attention due to their unique advantages in regulating the interaction between surfaces and liquids.

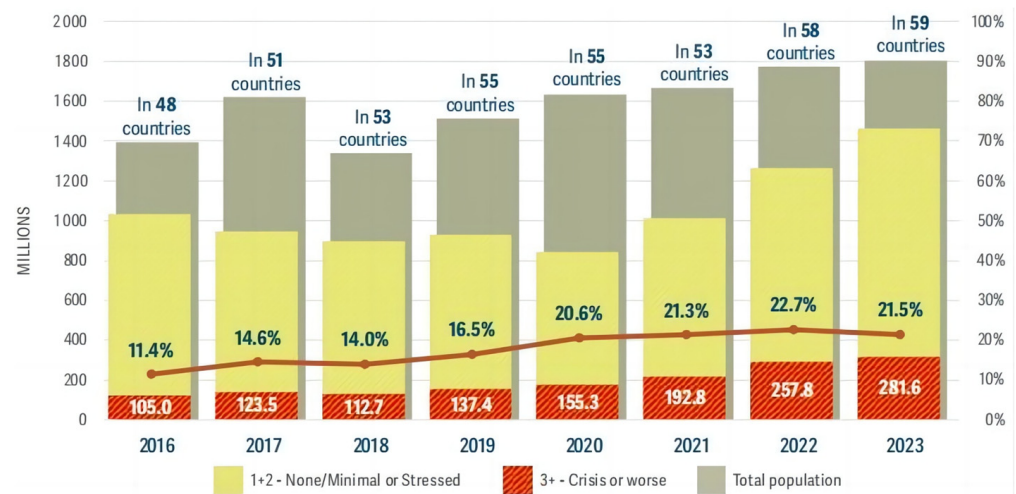


Figure 1. Numbers of people and share of the analyzed population in GRFC countries/territories facing high levels of acute food insecurity, 2016–2023.

Surface wettability, first theorized by Thomas Young in 1805, has driven advancements in material science, particularly in understanding how surface properties influence interactions with water and other substances [26–28]. Recent studies have focused on super-wetting materials inspired by natural phenomena like lotus leaves and butterfly wings, as shown in Figure 2.

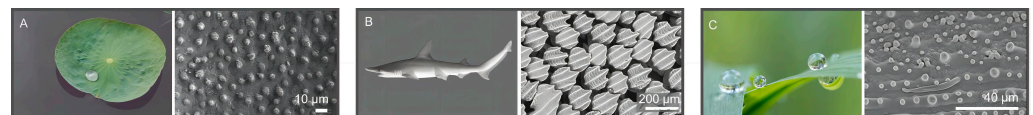


Figure 2. (A) Photograph of a lotus leaf and SEM image of its microstructures [29]. (B) Photograph of a shark and SEM image of shark skin microstructures [30]. (C) Photograph of droplets on rice leaves and SEM image of rice leaf microstructures [31].

The preparation and application of super-wetting materials have been extensively studied [32–36]. Zhang [37] provided a detailed introduction to the research progress of anti-fouling superhydrophilic materials, covering the design of superhydrophobic surfaces, superhydrophilic surfaces, and superhydrophilic/underwater superoleophobic surfaces, and discussed their anti-fouling mechanisms. Zhang [38] summarized the significant advancements in the field of two-dimensional nanomaterials over the past decade, focusing on innovations in bio-inspired two-dimensional photonic structures, energy nanomaterials, and super-wetting materials, while also discussing the challenges and opportunities faced in the development of bio-inspired materials for sustainable energy and environmental technologies. Guo [39] reviewed the latest developments in functionalized bio-inspired metal-derived super-wetting surfaces, with a particular focus on their practical applications in industrial production.

However, the existing research has largely focused on the specific technological applications or performance evaluations of super-wetting materials. Although these stud-

ies have revealed the immense potential of super-wetting materials in areas such as self-cleaning [40–42], droplet manipulation [43–45], drag reduction [46–48], anti-reflection [49–51], oil–water separation [52–57], and fog and ice prevention [58–62], and pointed out the challenges they face, such as mechanical durability, chemical stability, oil resistance, fabrication complexity, and cost-effectiveness [63–67], there has been a lack of systematic reviews and comprehensive analyses in this field, especially in terms of hotspot distribution, changes in research focus, and development trends.

This paper aims to fill this gap by using a bibliometric analysis and knowledge graph visualization techniques to deeply analyze the current research trends, key contributors, and future development directions. Furthermore, this paper explores the multiple applications of super-wetting materials in agricultural engineering, particularly their potential in agricultural films, controlled-release fertilizers, pesticide spraying, agricultural tillage, and drip irrigation systems, with the aim of providing theoretical support and a technical reference for advancing sustainable agricultural practices.

2. Bibliometric Analysis of Super-Wetting Materials

2.1. Data Sources and Research Methodology

In the current research landscape, systematically analyzing the existing literature to identify research trends and construct knowledge networks is of paramount importance. To ensure that this manuscript makes a significant scientific contribution to the field of super-wetting materials, the Web of Science was selected as the literature retrieval database. The search terms “super-wetting”, “superhydrophobic”, and “superhydrophilic” were established, using the “Exact” search mode and “WOS Core Collection” as the source type. Following a thorough database search, proofreading, and literature screening, a total of 23,259 valid research documents were obtained.

To further enhance the accuracy and scientific rigor of our findings, this study employed CiteSpace software 6.3R1 for a bibliometric analysis. This tool facilitates the generation of scientific knowledge graphs for specific knowledge areas through a multi-view data analysis, encompassing the clustering status, key nodes, evolution paths, and multidimensional scales.

Through a co-occurrence analysis, we can intuitively and efficiently integrate relevant literature, swiftly access core information in a particular research domain, and gain a deeper understanding of developments and trends within that area [68,69]. This process not only reveals the interrelationships among keywords and authors, but it also effectively identifies significant research outcomes and potential future directions in the field of super-wetting materials. Such an analysis ensures that this manuscript possesses sufficient depth and breadth in its scientific contributions, thereby advancing further research in related areas.

2.2. Time-Zone Distribution

The number of publications can reflect the research heat of a certain topic to a certain extent, and the time-zone distribution of research on super-wetting materials is shown in Figure 3.

It can be seen from Figure 3 that the research publications on super-wetting materials show an increasing trend on the whole, especially from 23 publications in 2003 to 2872 publications in 2022, indicating that the research on super-wetting materials has been given attention by more and more scholars.

2.3. Analysis of Research Institutions and Authors

The co-occurrence network of research institutions and authors can be used to visualize the distribution of research power and the cooperation relationship between research groups in a certain field. The retrieved documents from the WOS core collection database were analyzed by the “Institution” function in CiteSpace, and the co-occurrence network of research institutes on super-wetting materials was obtained, as shown in Figure 4.

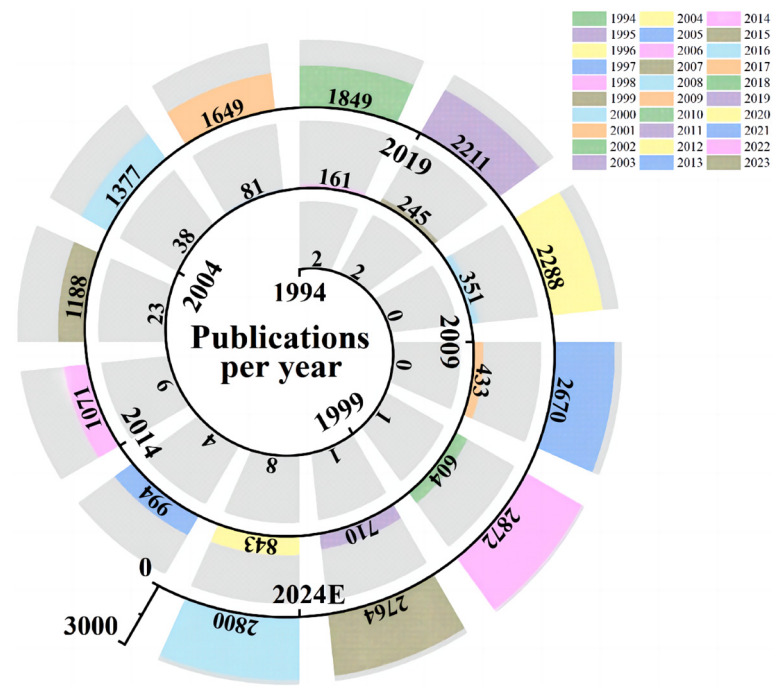


Figure 3. Time-zone distribution of publications on super-wetting materials.

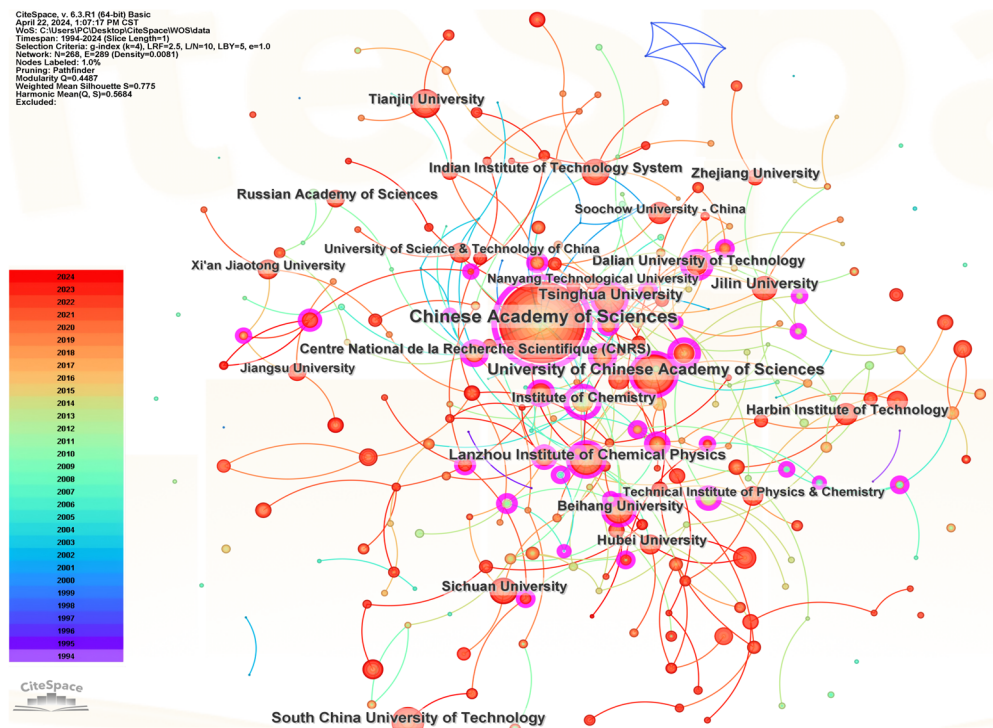


Figure 4. Co-occurrence network of research institutions on super-wetting materials.

It can be seen from Figure 4 that the overall development of academic organizations in the field of super-wetting materials research is relatively mature, and academic communications between research institutions are relatively frequent, which has formed an obvious cluster effect of academic research. Among them, the top 10 research organizations in terms of publications are shown in Table 1.

Table 1. Research organizations in terms of publications (top 10).

Publications	Centrality	Initial Year	Research Institution
2256	0.32	2001	Chinese Academy of Sciences
771	0.05	2006	University of Chinese Academy of Sciences
566	0.01	2006	Lanzhou Institute of Chemical Physics
506	0.07	2005	Tsinghua University
483	0.01	2009	South China University of Technology
442	0.05	2005	Jilin University
385	0.05	2011	Indian Institute of Technology
380	0.03	2009	Beijing University of Aeronautics and Astronautics
366	0.24	2003	French National Center for Scientific Research
345	0.03	2010	Harbin Institute of Technology

It can be seen from Table 1 that, among the top 10 research institutions, Chinese institutions accounted for 8 seats, and the number of publications of the Chinese Academy of Sciences is significantly higher than that of other institutions, indicating that China has shown strong research power in the research of super-wetting materials. The retrieved literature was analyzed by using the “Author” function in CiteSpace to obtain the co-occurrence network of authors, as shown in Figure 5.

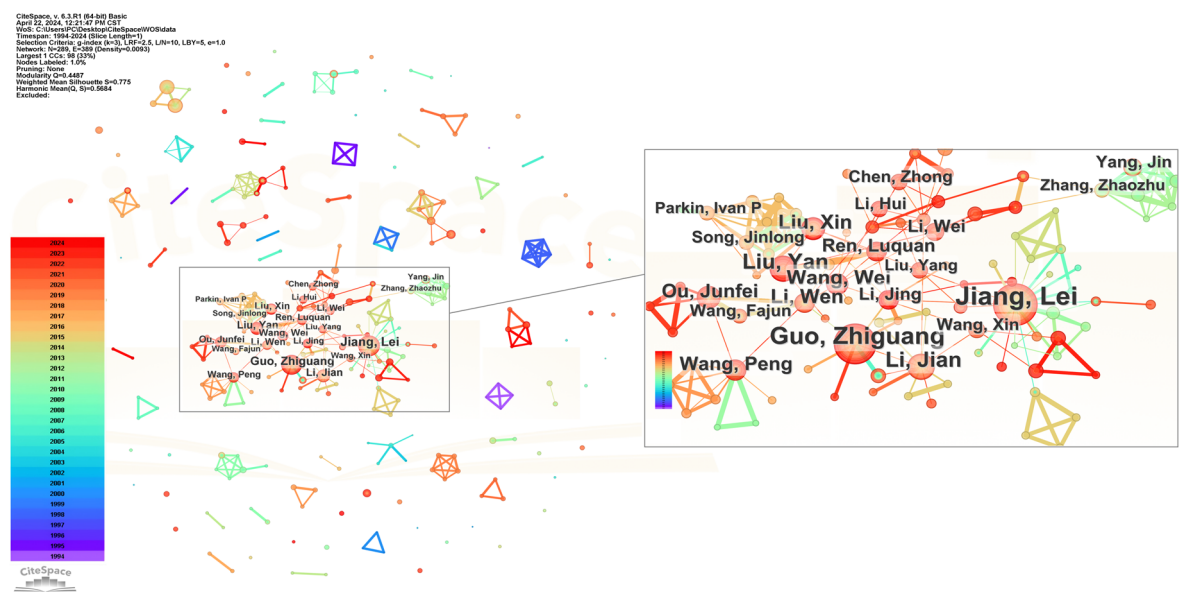


Figure 5. Co-occurrence network of authors on super-wetting materials.

It can be seen from Figure 5 that the academic atmosphere among scholars in the field of super-wetting materials is relatively independent and not closely connected on the whole; it is mainly based on the connection between different universities in the same region and different scholars in the same university. Among all the scholars, Jiang Lei’s team has made a greater contribution to the field, which can also be proven by the citation frequency (top 20) of the publications, as shown in Table 2.

Table 2. Citation frequency of publications on super-wetting materials (top 20).

No.	Citations	Citing Article
1	1570	Feng L, 2008, LANGMUIR, V24, P4114, DOI 10.1021/la703821h [70]
2	1457	Lu Y, 2015, SCIENCE, V347, P1132, DOI 10.1126/science.aaa0946 [71]
3	1415	Xue Z, 2011, ADV MATER, V23, P4270, DOI 10.1002/adma.201102616 [72]
4	1394	Feng L, 2004, ANGEW CHEM INT EDIT, V43, P2012, DOI 10.1002/anie.200353381 [73]
5	1115	Jiang L, 2004, ANGEW CHEM INT EDIT, V43, P4338, DOI 10.1002/anie.200460333 [74]
6	1088	Wang D, 2020, NATURE, V582, P55, DOI 10.1038/s41586-020-2331-8 [75]
7	971	Xue Z, 2014, J MATER CHEM A, V2, P2445, DOI 10.1039/c3ta13397d [76]
8	961	Zhang W, 2013, ADV MATER, V25, P2071, DOI 10.1002/adma.201204520 [77]
9	946	Zheng Y, 2007, SOFT MATTER, V3, P178, DOI 10.1039/b612667g [78]
10	834	Gao X, 2007, ADV MATER, V19, P2213, DOI 10.1002/adma.200601946 [79]
11	775	Guo Z, 2011, J COLLOID INTERF SCI, V353, P335, DOI 10.1016/j.jcis.2010.08.047 [80]
12	743	Zhang F, 2013, ADV MATER, V25, P4192, DOI 10.1002/adma.201301480 [81]
13	717	Qian BT, 2005, LANGMUIR, V21, P9007, DOI 10.1021/la051308c [82]
14	714	Liu Y, 2014, NAT PHYS, V10, P515, DOI 10.1038/NPHYS2980 [83]
15	667	Jin MH, 2005, ADV MATER, V17, P1977, DOI 10.1002/adma.200401726 [84]
16	646	Zhang W, 2014, ANGEW CHEM INT EDIT, V53, P856, DOI 10.1002/anie.201308183 [85]
17	593	Tao M, 2014, ADV MATER, V26, P2943, DOI 10.1002/adma.201305112 [86]
18	591	Wang X, 2013, MATER TODAY, V16, P229, DOI 10.1016/j.mattod.2013.06.005 [87]
19	572	Si Y, 2015, ACS NANO, V9, P3791, DOI 10.1021/nn506633b [88]
20	564	Kulinich SA, 2011, LANGMUIR, V27, P25, DOI 10.1021/la104277q [89]

As can be seen from Table 2, 12 of the 20 most frequently cited articles in the literature on super-wetting materials are from Jiang Lei's team, which shows its important academic strength in this field, and scholars who want to engage in super-wetting research in the future should pay more attention to the research results of this team.

2.4. Co-Occurrence Networks of Keywords

Keywords are a concise and distinctive representation of a research topic in a field, and the analysis of keywords in publications can be used to explore the main theme of the research [90]. When two keywords appear more frequently in the same literature, it means that these two topics are more closely related to each other. Therefore, a keyword co-occurrence network analysis can be used to determine the relationship between the topics and their disciplinary hierarchy in the discipline represented by the literature set. Figure 6 shows the keyword co-occurrence network of research on the topic of super-wetting materials. The node size in the network represents the keyword frequency; the greater the frequency, the larger the node, and the closer the relationship between research topics. The line color corresponds to the year on the right side of the graph; the brighter the color, the more recent the year, which is used to mark which major keywords are available in each year.

As can be seen in Figure 6, wettability, surfaces, fabrication, and oil–water separation appear with a high frequency and are the main core keywords in the field. To reveal the evolution trend among the hotspots in the research field of super-wetting materials more comprehensively, 23,259 literature samples were statistically analyzed by using the co-occurrence analysis method; a total of 281 core high-frequency keywords were obtained and the keywords with top 10 frequencies were statistically sorted out according to the year, as shown in Table 3. The greater the centrality, the stronger the vitality, dominance, and influence of the keyword in the research vein and the development trend of super-wetting materials, and the greater the recognition and scalability of the corresponding research results.

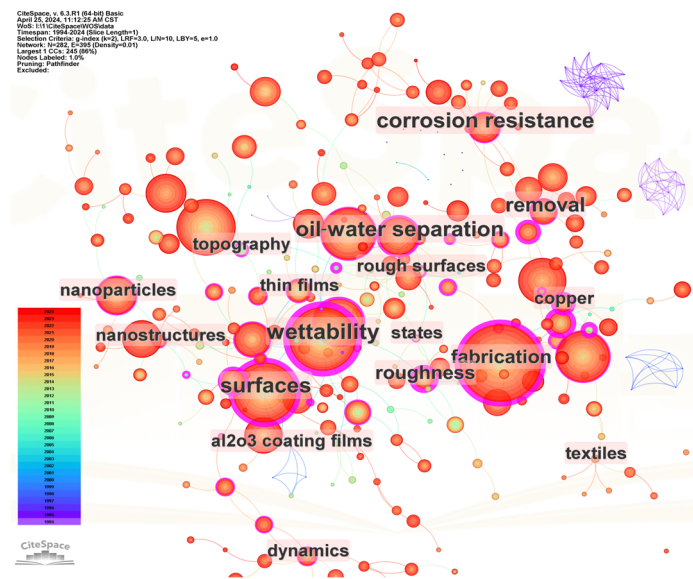


Figure 6. Co-occurrence network of keywords on super-wetting materials.

Table 3. High-frequency keywords on super-wetting materials (top 10).

Initial Year	Keywords	Frequency	Centrality
1994	Water	3047	0.14
2000	Surfaces	5941	0.77
2003	Films	3467	0.22
2004	Wettability	4038	0.98
2005	Fabrication	5470	0.67
	Coatings	2606	0.12
2006	Superhydrophobic surfaces	5102	0.14
	Nanoparticles	1580	0.12
2014	Oil–water separation	2645	0.66
	Corrosion resistance	1976	0.15

It can be seen from Table 3 that the research on super-wetting materials has gone through recognition and preparation process research in the early stage and then to functional modification and performance analysis research later. The relevant research themes and hotspots in the iteration process are not isolated, but are interrelated, and it is precisely the back-and-forth correlation that directly promotes the evolutionary process of research development. Meanwhile, the aspects of centrality, wettability, surface, oil–water separation, and fabrication show a strong academic influence in the field of super-wetting materials research.

Burst terms are terms that appear in the literature with large changes in frequency and number over a short period. By detecting and analyzing the burst terms in the research of super-wetting materials, we can gain an intuitive understanding of the research hotspots and their connotation migration in different periods. The burst analysis of the keywords of super-wetting materials from 1994 to 2024 is shown in Table 4.

It can be seen in Table 4 that half of the top 10 keywords have been studied for more than 10 years, indicating that the field has attracted long-term focus and heat from scholars. According to the order of emergence intensity, films have the highest intensity (267.33); according to the order of time duration, contact angle has been in the spotlight for the longest period (2004–2017); and according to the order of time proximity, oil–water separation is the newest hotspot of research (2016–2024).

Table 4. Keywords with the strongest citation bursts (top 10).

Keywords	Strength	Begin	End	1994–2024
Films	267.33	2003	2015	
Roughness	210.51	2005	2015	
Contact angle	190.06	2004	2017	
Lotus	145.26	2005	2014	
Oil–water separation	138.24	2016	2024	
Water repellent	129.94	2004	2015	
Wettability	93.86	2004	2010	
Super hydrophobic surfaces	65.55	2005	2013	
Solid surfaces	56.69	2006	2015	
Self-assembled monolayers	52.25	2007	2017	

3. Application of Super-Wetting Materials in Agricultural Engineering

Wetting is a fundamental phenomenon observed in nature. By examining the surface wettability of plants and animals, researchers have uncovered the relationship between surface wettability and structural composition, leading to innovative advancements in material science. Super-wetting materials, inspired by these natural phenomena and enhanced through advanced preparation techniques, have the potential to revolutionize various fields [91–94]. In agricultural engineering, these materials offer promising solutions to key challenges, particularly in crop protection, fertilizer efficiency, irrigation, etc., as shown in Table 5, thereby supporting the development of sustainable and efficient agricultural practices.

Table 5. The application of super-wetting materials in agricultural engineering.

Application Area	Super-Wetting Material Used	Key Features	Benefits	Challenges
Agricultural Films	Superhydrophobic, dust-resistant composite films	Optimized light transmission, insulation, and mechanical strength	Improved crop protection, resource management, enhanced film longevity	High production costs, complexity, limited accessibility for small-scale farmers
Anti-Fog Films	Micro/nanostructured surfaces (titanium dioxide nanoparticles)	Anti-fogging, energy management with carbon-based/polymer composite films	Maintains optimal light conditions, reduces energy loss in greenhouses	Long-term stability and ecological safety of surfactants need evaluation
Water Management	Janus films	Superhydrophobicity, photothermal properties	Reduces water loss through evaporation, optimizes irrigation	Durability under extreme weather, performance in real-world settings
Smart Greenhouses	Superhydrophobic, electrostatically negative layer	Self-cleaning friction nano-generator for raindrop energy harvesting	Improves energy efficiency, enhances environmental control	High maintenance cost, integration complexity
Controlled-Release Fertilizers	Hydrophobic, eco-friendly, self-healing bio-nanocomposites	Precise control over nutrient release	Enhanced nutrient efficiency, reduced environmental impact	Long-term stability, production scalability, environmental impact of coatings
Pesticide Spraying	Green pesticide additives, flexible polymers with surfactants	Improved droplet retention, enhanced pesticide coverage	Reduces pesticide waste, improves pest control efficiency	Long-term effects on non-target organisms, potential toxicity concerns

Table 5. Cont.

Application Area	Super-Wetting Material Used	Key Features	Benefits	Challenges
Microchannel Heat Transfer	Micro/nanostructured surfaces	Improved boiling heat transfer characteristics	Energy-efficient agricultural processes (e.g., grain storage, drying)	Manufacturing and maintenance complexity, durability concerns
Farm Cleanliness	Superhydrophobic surfaces (laser-processed)	Minimized adhesion of contaminants, enhanced farm hygiene	Reduces labor-intensive cleaning tasks, improves hygiene	Real-world effectiveness over extended periods, environmental impact of synthetic materials
Irrigation Systems	Hydrophilic/hydrophobic gradient surfaces, superhydrophobic microstructures	Optimized water collection, reduced clogging, improved water distribution	Water conservation, enhanced irrigation efficiency in water-scarce regions	Scalability, long-term performance, and environmental effects need evaluation

3.1. Application in Agricultural Films

Agricultural films are vital for improving soil conditions, protecting crops, and increasing yields due to their excellent heat preservation and moisture retention properties [95]. As agricultural modernization progresses, the application of these films continues to expand. The integration of super-wetting materials into agricultural films represents a significant advancement in agricultural engineering, enhancing crop protection and improving resource management. According to the China Plastics Processing Industry Association, the output of agricultural films in China is expected to reach 1.05 million tons by 2026, underscoring their growing importance in agricultural production. Meanwhile, this trend underscores the need for continuous improvement in film technology to meet diverse agricultural demands.

To meet the diverse demands of different climates, crops, and environmental conditions, the functionalization and modification of agricultural films have become crucial. For example, Mi et al. [96,97] developed superhydrophobic, dust-resistant composite films that are also durable, transparent, and thermally stable, as shown in Figure 7A. These films are designed to optimize light transmission, insulation, and mechanical strength, providing a robust experimental foundation for the development of high-performance, cost-effective agricultural films. The development of such films demonstrates significant innovation in material science, potentially leading to longer-lasting and more efficient agricultural practices. However, the production processes may be complex and costly, which could limit accessibility for small-scale farmers. Zhang et al. [98] extended the lifespan of agricultural paper covers by creating superhydrophobic surfaces, thereby enhancing their resistance to water and extending their usability in the field. This advancement offers a practical solution to the common issue of the premature degradation of agricultural covers. Nonetheless, the environmental impact of increased plastic use in these treatments raises concerns, as non-biodegradable materials could contribute to pollution. Sui et al. [99] prepared anti-fog films with an excellent performance by using anti-fog droplet agents (Span 20 and Tween 20) and co-modified nano-TiO₂ based on the research foundation in the construction of carbon-based/polymer composite films and their energy management. While anti-fog technology is beneficial for maintaining optimal light conditions in greenhouses, the long-term stability and ecological safety of the surfactants used must be thoroughly evaluated to prevent unintended consequences in agricultural ecosystems. Furthermore, leveraging research on carbon-based/polymer composite films and their role in energy management, Chen et al. [100] introduced a simple, efficient, and scalable method to fabricate Janus films. By embedding hierarchical nanostructured wax soot partially into polydimethylsiloxane (PDMS) elastomers, they achieved films with a remarkable superhydrophobicity and photothermal properties, as illustrated in Figure 7B. In agricultural applications, these Janus

films could be used for water management on crop leaves, reducing the water loss through evaporation and optimizing the water usage in irrigation systems. Additionally, their photothermal properties can help regulate the temperature on plant surfaces, protecting crops from extreme temperatures and enhancing their growth efficiency. These films have the potential to reduce water loss through evaporation and optimize irrigation. However, the durability of these coatings under extreme weather conditions and their performance in real-world agricultural settings require further investigation. In smart greenhouses, the integration of super-wetting materials into films plays a crucial role in energy management and environmental control. Ping et al. [101,102] innovatively modified greenhouse films to incorporate a superhydrophobic, electrostatically negative layer that powers a self-cleaning friction nano-generator (RDE-TENG) for harvesting raindrop energy, as shown in Figure 7C. This system not only provides a stable power source for monitoring devices, but it also enables intelligent environmental control, guiding agricultural production towards greater efficiency and sustainability. This innovative approach not only contributes to energy efficiency, but also enhances environmental control within greenhouses. However, the complexity of integrating such systems may pose challenges in terms of maintenance and initial investment costs, particularly for smaller farming operations.

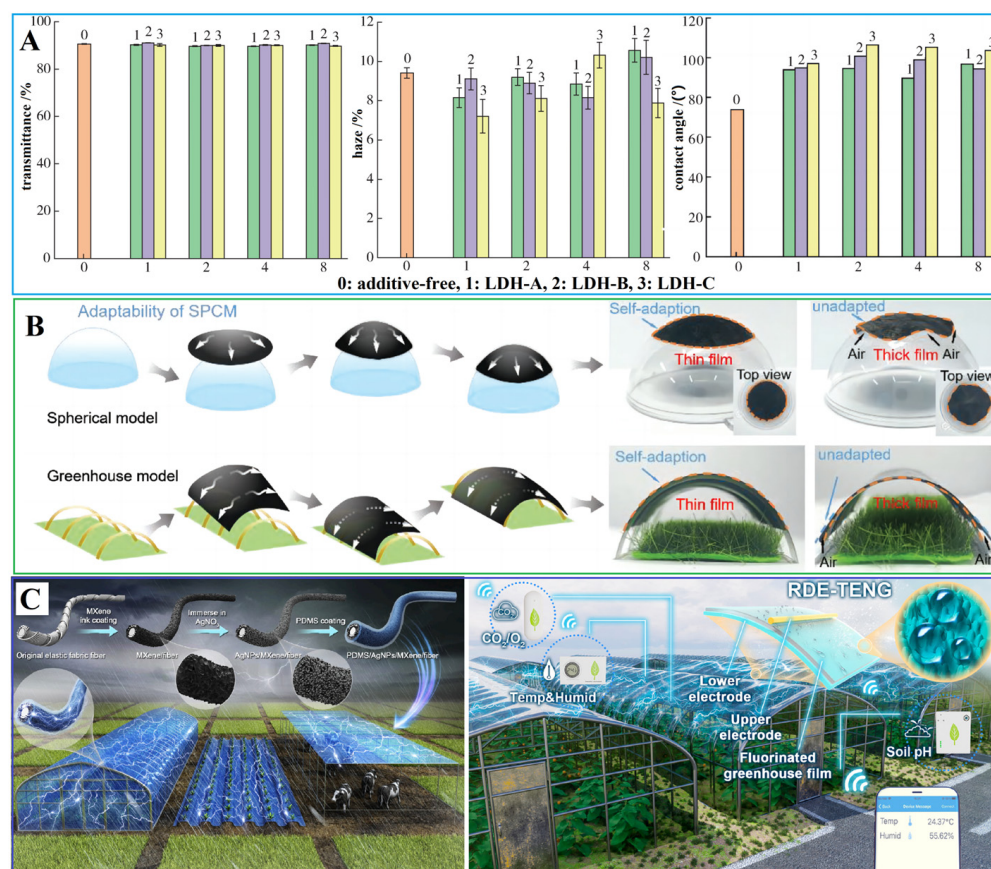


Figure 7. (A) Transmittance, haze, and contact angle of pristine PE film and PE/LDH composite films. (B) Adaptive images of thin ($\approx 50 \mu\text{m}$) and thick ($\approx 150 \mu\text{m}$) SPCM surfaces in hemispheres and greenhouse models. (C) The fabric TENG yarn, and its application in the agriculture field.

Overall, while the innovations presented in these studies showcase significant advancements in agricultural film technology, several potential drawbacks must be considered. The reliance on synthetic materials and chemicals can lead to environmental concerns, particularly if these materials are not biodegradable. Sustainable alternatives should be explored to mitigate this impact. Advanced materials often come with higher production costs, which may limit their accessibility to smallholder farmers. Future research should focus on

developing cost-effective solutions that are scalable for diverse agricultural settings. The effectiveness of these films under different environmental conditions needs thorough testing. Real-world trials can help identify any limitations in their durability or effectiveness, ensuring that these innovations can be reliably adopted in various agricultural practices.

3.2. Application in Controlled-Release Fertilizers

Fertilizers are essential for enhancing crop yields and ensuring food security. However, the overuse of chemical fertilizers has led to environmental degradation and inefficient nutrient utilization. Controlled-release fertilizers (CRFs), enhanced with super-wetting materials, offer a solution to these problems by regulating nutrient release according to the plant needs [103–105].

Yang et al. [106–113] pioneered the use of super-wetting modification technology to develop hydrophobic, eco-friendly, and self-healing bio-nanocomposites, as shown in Figure 8A. These materials enable precise control over nutrient release, improving the efficiency and environmental impact of CRFs. This innovation highlights the potential for environmentally friendly materials to enhance agricultural productivity. However, the long-term stability and effectiveness of these bio-nanocomposites under various environmental conditions must be investigated to ensure their practical viability. Zou et al. [114,115] further advanced this technology by developing a bio-based coated urea (BCU) with enhanced water resistance and nitrogen retention, providing a sustainable alternative to traditional petrochemical-based fertilizers, as shown in Figure 8B. The development of BCU represents a significant step toward sustainable fertilization practices. Nevertheless, the scalability of producing bio-based fertilizers at a competitive cost compared to traditional petrochemical fertilizers remains a challenge that needs to be addressed. Zhang et al. [116,117] conducted research on the fabrication of superhydrophobic composites specifically designed for controlled-release fertilizers (CRFs) using advanced coating technology. Their work delved into the microstructure of these composite coatings, analyzing factors such as the thermal stability, the surface hydrophobicity, and the release properties of the coated fertilizers. They also investigated the impact of these materials on crop growth in real agricultural settings. Their study highlights how the integration of superhydrophobic materials can significantly enhance the efficiency of CRFs, reducing nutrient loss and optimizing water usage, as shown in Figure 8C. The integration of super-wetting materials into CRFs offers several advantages, including reduced nutrient leaching, improved crop growth, and minimized environmental impact. This research underscores the importance of understanding the microstructural characteristics of coatings in enhancing fertilizer performance. However, while their studies demonstrate an improved nutrient release efficiency, the potential environmental impacts of the coatings, particularly their biodegradability and interaction with soil microorganisms, require further assessment.

Overall, the application of super-wetting materials in controlled-release fertilizers represents a major advancement in agricultural practices, promoting efficiency and sustainability. While the above studies have revealed important findings and enhanced our understanding of controlled-release fertilizers, issues such as their potential production costs and accessibility, as well as the long-term effects of super-wetting materials on soil health and microbial communities, are critical to ensuring their long-term viability and environmental safety. Continued research in this area should focus on optimizing the production methods, evaluating ecological impacts, and developing strategies to integrate these innovations into traditional agricultural practices. By doing so, the agricultural sector can better leverage the advantages of super-wetting materials and contribute to sustainable food production and environmental management.

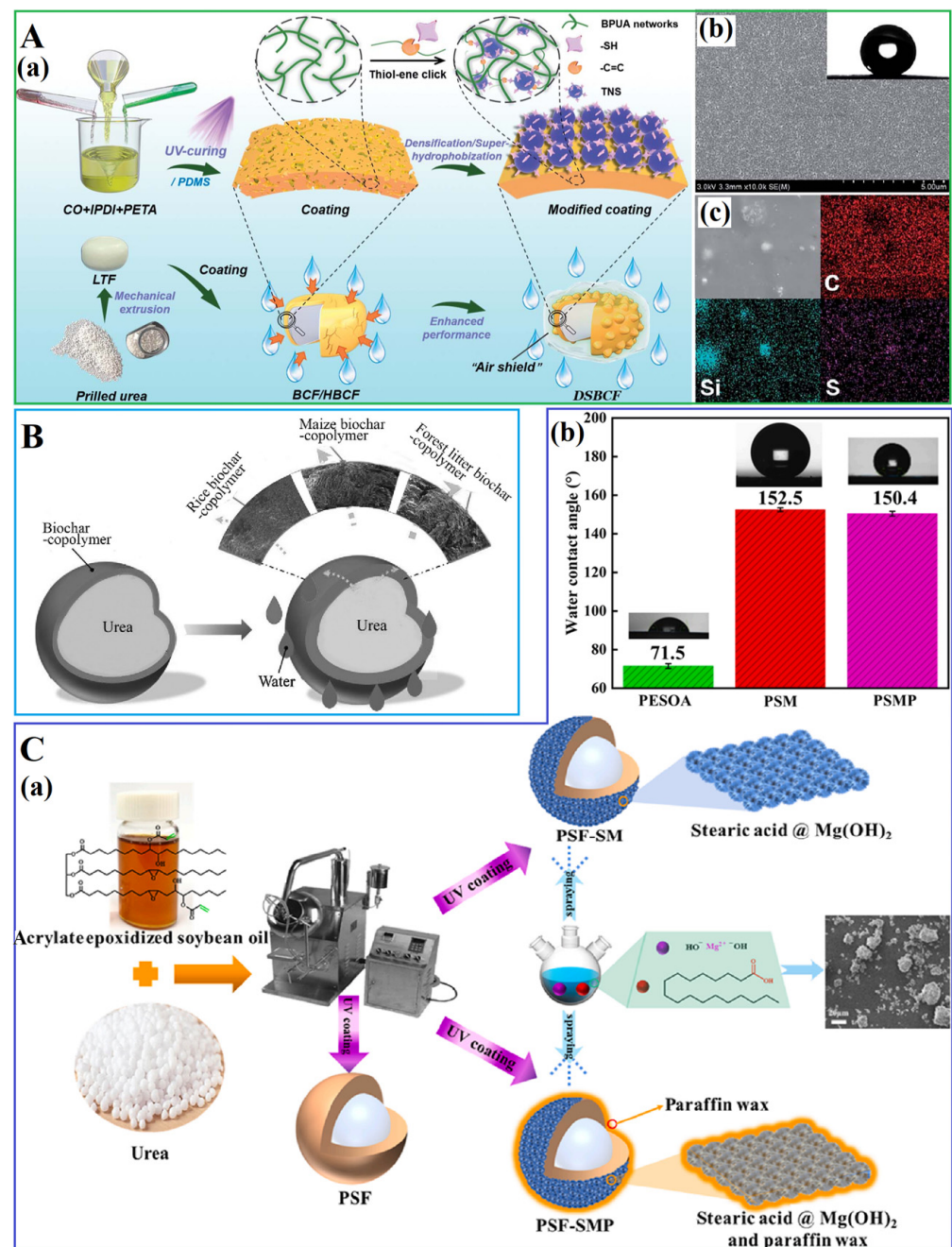


Figure 8. (A) (a) The design and working principle of the biopolymer-coated large tablet controlled-release fertilizer. (b) SEM images of DSBCF with the corresponding WCAs. (c) EDS maps corresponding to the SEM images and AFM images. (B) Hydrophobic bio-based polyurethane coating. (C) (a) Preparation process of PSF, PSF-SM, PSF-SMP. (b) Contact angle analysis of PSEOA, PSM, and PSMP.

3.3. Application in Pesticide Spraying

Effective pest control is essential for protecting crops and ensuring high yields [118]. However, conventional pesticide spraying methods often result in significant waste and environmental pollution due to poor adhesion and coverage on plant surfaces. Super-wetting materials have been applied to address these challenges, improving the efficiency and environmental safety of pesticide applications [119].

Du et al. [120–126] researched green pesticide additives that enhance the deposition and adhesion of spray droplets on plant surfaces, as shown in Figure 9A. Their findings

indicate that optimizing pesticide formulations can significantly increase the pest control effectiveness while reducing environmental contamination. This research is vital in demonstrating how environmentally friendly additives can improve the pesticide application efficiency. However, the long-term effects of these additives on non-target organisms and soil health need further investigation to ensure ecological safety. Song et al. [127,128] introduced a strategy that combines flexible polymers with surfactants to improve droplet retention and coverage on plants, as shown in Figure 9B. Their approach enhances the impact of pesticides, suggesting a new avenue for optimizing pesticide formulations. This innovation could lead to more efficient pest management practices; however, the durability and potential environmental effects of these polymers and surfactants, especially after degradation, require a thorough assessment to avoid unintended consequences. Wang et al. [129] tackled the challenge of pesticide waste on the underside of leaves by developing a bile salt/cationic surfactant with nanoscale hydrophilic/hydrophobic domains, as shown in Figure 9C. This ensures effective pesticide deposition on varying surfaces. This advancement is significant, as it addresses a common inefficiency in pesticide applications. However, the scalability of producing such surfactants and their potential toxicity to beneficial insects and aquatic ecosystems must be carefully evaluated. Jia et al. [130] developed a green pseudo-polymeric film surfactant using fatty acids and hexamethylenediamine to control droplet behavior on superhydrophobic surfaces. This innovation aids in optimizing pesticide applications. While this surfactant presents a promising solution to droplet management, the stability of the film and its long-term environmental impact, particularly in terms of biodegradability and interactions with soil microorganisms, must be further explored. Hu et al. [131,132] created a nano pesticide delivery system that enhances foliar deposition and enables controlled release, providing a sustainable method for pest control, as shown in Figure 9D. This system shows great potential for increasing the pesticide effectiveness while minimizing the environmental impact. However, the development and long-term effects of nanomaterials in agricultural settings need thorough investigation, especially regarding their interaction with soil and water systems.

Overall, the application of super-wetting materials in pesticide spraying represents a significant advancement in agricultural practices, as their enhanced droplet adhesion and coverage can lead to more effective pest control, reduced amounts of pesticides required, and minimized waste. And the focus on green additives and materials aims to reduce the ecological footprint of pesticide applications and promote sustainable agricultural practices. Despite these benefits, the ecological consequences of using novel surfactants and polymers in pesticide formulations remain largely unknown. Continued monitoring and research are essential to assess their effects on non-target organisms and soil health. At the same time, the development of advanced pesticide formulations may increase production costs, which may limit their use by small farmers. Strategies to reduce costs while maintaining effectiveness are necessary for widespread adoption.

3.4. Applications in Other Areas of Agricultural Engineering

Super-wetting materials have also been applied to various other aspects of agricultural engineering, such as microchannel heat transfer, farm cleanliness, and drip irrigation systems.

Luo et al. [133] investigated the use of micro/nanostructured surfaces to improve the boiling heat transfer characteristics of microchannels, as shown in Figure 10A. This innovation has promising applications in controlling temperatures in grain storage silos, agricultural drying systems, and solar water heating systems, contributing to more energy-efficient agricultural processes. While this advancement has the potential to optimize energy use, the complexity of manufacturing and maintaining micro/nanostructured surfaces in practical applications may pose challenges. Additionally, the durability of these structures under varying environmental conditions needs further exploration to ensure their long-term effectiveness.

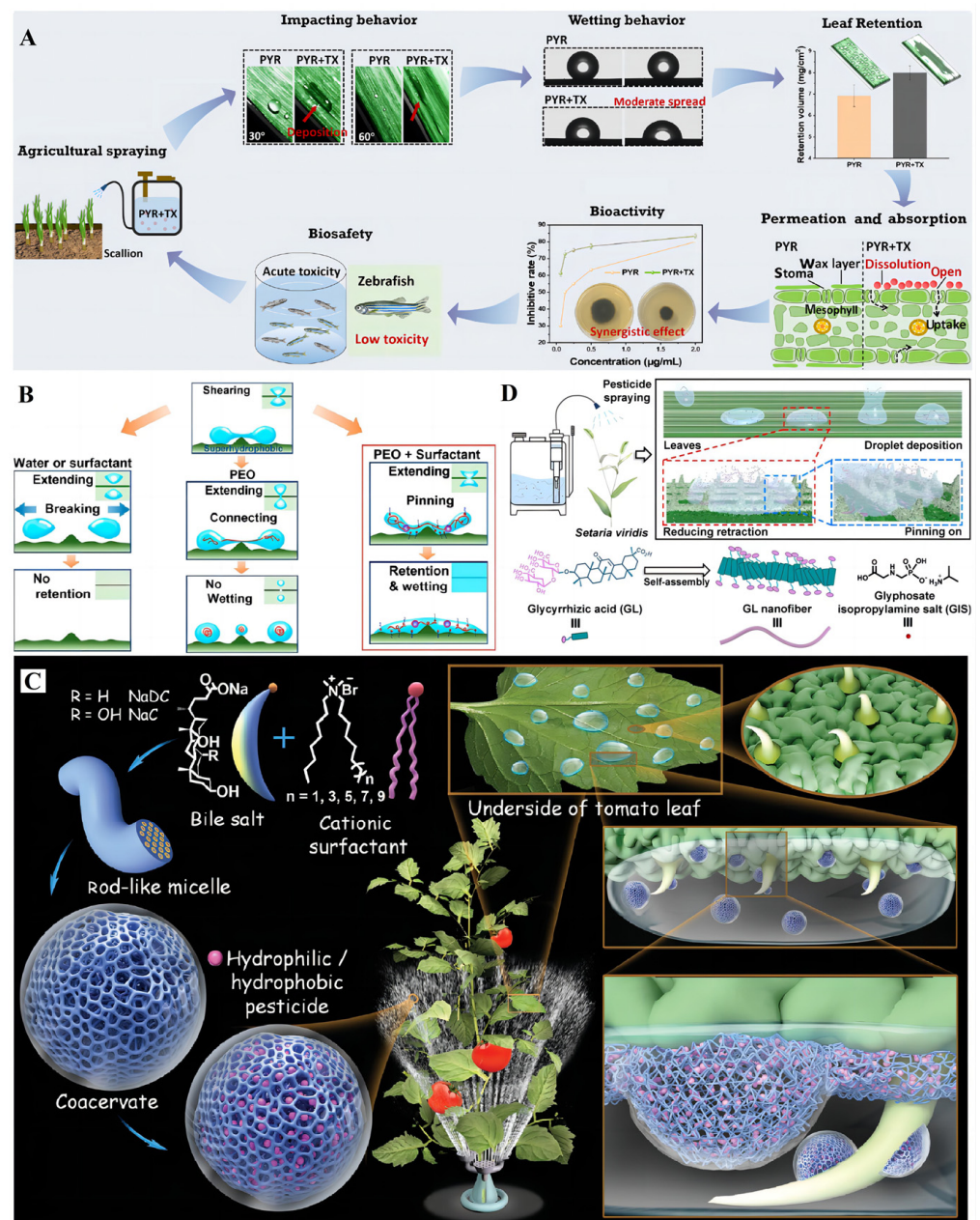


Figure 9. (A) Schematic of the impact, wetting, adhesion, and leaf retention behaviors of pyra-clostrobin (PYR) droplets containing the surfactant Triton X (TX) series on hydrophobic scallion leaf surfaces. (B) Underlying mechanism for enhancing asymmetric impact deposition using binary additives on a single wired superhydrophobic surface. (C) Schematic of the strategy for controlling a water-based pesticide spray on the superhydrophobic abaxial side of tomato leaves. (D) Top: schematic representation of impact, retraction, and deposition of droplets containing GIS and 1D nanofibers from GL on hydrophobic weed leaves. Bottom: chemical structures of glyphosate isopropylamine salt (GIS), glycyrrhizic acid (GL), and GL nanofibers.

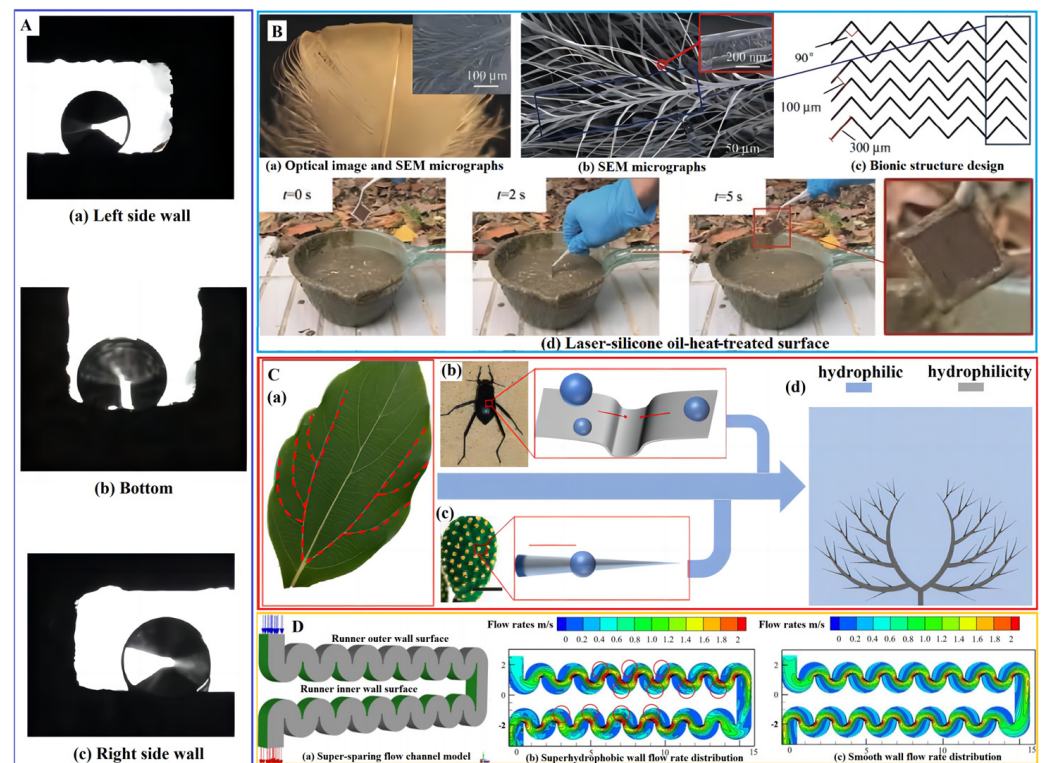


Figure 10. (A) Schematic diagram of microchannel superhydrophobic surface contact angle. (B) Morphology observation of duck feather structure, design of bionic surface, anti-fecal adhesion, and self-cleaning test. (C) Source of inspiration for designing a mist-collecting surface; (a) camphor tree leaf vein; (b) desert beetle and its back catchment map; (c) cactus and its spikes' catchment map; and (d) fog catchment surface. (D) Modeling the flow channel of a superhydrophobic wall irrigator and its flow rate distribution.

In livestock farming, maintaining cleanliness is crucial for preventing disease and promoting animal health [134,135]. Traditional cleaning methods are labor-intensive and often insufficient. Wang et al. [136] tackled cleanliness in livestock farming by developing superhydrophobic surfaces through laser processing technology, as shown in Figure 10B. These surfaces minimize the adhesion of contaminants, reducing the need for labor-intensive cleaning methods and enhancing overall farm hygiene. Although this technology improves hygiene, its effectiveness in real-world settings over extended periods must be assessed. Moreover, the environmental impact of using synthetic materials in agricultural settings, particularly their biodegradability and interaction with farm waste, should be evaluated to prevent ecological harm.

In water-scarce regions, efficient irrigation is vital for crop survival and yield [137–139]. Ren et al. [140] designed a hydrophilic/hydrophobic gradient surface inspired by natural structures to enhance fog water collection for drip irrigation, as shown in Figure 10C, which is particularly beneficial in arid regions, where water conservation is crucial. While this technique shows promise for efficient water management, the scalability of implementing such structures in diverse agricultural contexts remains a concern. Additionally, the long-term performance and maintenance of these gradient surfaces need further investigation to ensure that they can withstand environmental challenges such as wind and dust. Liu et al. [141,142] further enhanced drip irrigation systems by integrating superhydrophobic microstructures into irrigator channels, effectively reducing clogging and improving the water distribution efficiency, as shown in Figure 10D. While integrating superhydrophobic microstructures enhances the irrigation efficiency, the potential downsides include the initial costs associated with upgrading existing irrigation infrastructure and the need for ongoing maintenance. Furthermore, the environmental effects of these microstructures

tures, particularly regarding their long-term durability and impact on soil health, require careful consideration.

Overall, the application of super-wettable materials in various aspects of agricultural engineering represents a significant advancement in improving efficiency and sustainability. The above studies show that these materials have the potential to address key challenges in temperature management, farm hygiene, water conservation, and irrigation efficiency. However, careful consideration of the potential drawbacks, including environmental impacts, scalability, and maintenance challenges, is critical to ensure the long-term viability of these innovations in agricultural practices. Future research should focus on optimizing these technologies to adapt to different agricultural environments, promoting sustainable practices while increasing productivity.

4. Discussion and Conclusions

Technological innovation plays a critical role in enhancing resource efficiency and driving industrial transformation, including within the agricultural sector. Each advancement in science and technology fosters innovation in agriculture, leading to transformative shifts in agricultural practices and the modernization of industrial structures. As highlighted in the United Nations report and corroborated by relevant literature, the ongoing scientific and technological revolution poses challenges for various countries and regions. Particularly, developing nations with limited agricultural science and technology infrastructure may struggle to keep pace with these innovations in their governmental and agricultural sectors. In this context, the development and application of new materials, especially super-wetting materials, are becoming an important driving force for agricultural technology innovation. With their unique physical and chemical properties, super-wetting materials can provide solutions in different agricultural scenarios, thereby improving the resource utilization efficiency and reducing negative impacts on the environment. They not only show great potential in traditional fields such as water resource management, fertilizer utilization, and pest control, but they also provide technical support for emerging fields such as precision agriculture and sustainable development.

This paper comprehensively and objectively synthesizes the research trajectory and development of super-wetting materials through a bibliometric and knowledge graph visualization analysis, and by studying the distribution of research publications, major institutions, and leading scholars. This study revealed that the research in the field of super-wetting materials has experienced remarkable growth, with key contributors, particularly Jiang Lei's team and leading Chinese institutions, making substantial academic contributions. Future research should focus on addressing scalability issues, exploring functional modifications, and driving the integration of super-wetting materials into industrial applications. By emphasizing interdisciplinary approaches and considering environmental sustainability, this field can continue to advance and play a pivotal role in solving global challenges such as energy conservation, water management, and environmental protection.

In addition, this research highlights the application of super-wetting materials in various agricultural fields such as films, fertilizers, pesticides, farming practices, and drip irrigation. The results show that super-wetting materials demonstrate significant potential across various sectors of agricultural engineering, offering innovative solutions for crop protection, water conservation, and sustainable agricultural practices. However, several challenges, including their environmental impact, production costs, scalability, durability, etc., must be addressed at the same time to ensure their long-term success in agricultural applications.

1. Future research should focus on the development of biodegradable, cost-effective, and scalable super-wetting materials. As the use of synthetic super-wetting materials could lead to long-term environmental issues, efforts should be directed towards creating materials that naturally break down without harming ecosystems. Additionally, exploring alternative, lower-cost fabrication methods will be critical to ensure that these technologies are accessible, particularly to small-scale farmers. Life cycle analyses of these materials,

from production to disposal, should also be conducted to evaluate their ecological footprint and overall contribution to sustainable agricultural practices.

2. To ensure the effectiveness of super-wetting materials in agricultural systems, research must prioritize testing their long-term durability and real-world performance under diverse environmental conditions. This includes assessing their mechanical stability, chemical resistance, and weather resilience in various climates and geographical and regional variations. Conducting real-world trials and field experiments will provide valuable insights into how these materials perform over extended periods and in challenging conditions, such as extreme weather events or fluctuating climates.

3. Future studies should explore the integration of super-wetting materials into smart agricultural systems. The integration of cross-disciplinary approaches from material science, environmental science, and agricultural engineering will enhance the development of materials that are not only durable, but also optimized for agricultural efficiency and environmental control. Research into innovations such as self-healing materials, smart responsive coatings, and nano-enhanced fertilizers should be prioritized to optimize crop yields, improve resource usage, and minimize the environmental impact.

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