Development of Hydrophobic Fabrics Modified with Graphene: A Systematic Review

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Pursuing fabric with hydrophobicity and self-cleaning properties has been a focal point across various applications. Graphene has emerged as a prominent contender for fabric modification to augment hydrophobicity. This study endeavors to conduct a systematic review of fabrics imbued with graphene for hydrophobic applications, concentrating on the most recent five years and employing the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-analyses). Articles were curated from reputable databases, including Scopus, Web of Science, and Science Direct. Following meticulous inclusion/exclusion criteria, thirty-seven studies were deemed eligible for inclusion in the review.
Keywords: Graphene. Fabric. Textile. Hydrophobic. Nanocomposite.

In recent years, nanotechnology has allowed the incorporation of nanoparticles into multifunctional textiles, adding new physical and chemical characteristics to fibers, threads, and fabrics. Fabrics with hydrophobic properties similar to lotus leaf surfaces have recently drawn the attention of researchers due to their significant potential for scientific and industrial applications [1-3].

Graphene has stood out recently due to its remarkable properties, such as fracture resistance, thermal conductivity, impermeability, and hydrophobicity. In addition to these applications, a wide range of graphene applications includes electrical conductivity [2-4], usage as flame retardants [5], energy storage and conversion [6], dye removal [7], and antibacterial function [8]. However, applying graphene to a polymeric matrix (fabric) remains a significant challenge for researchers, particularly when considering high-scale production and low cost.

PRISMA, a reporting guideline for systematic reviews and meta-analyses, was developed to improve reporting quality. It helps plan and document review methods [10]. Systematic reviews synthesize knowledge in afield, identifying research gaps and evaluating theories [11,12]. Our study systematically reviews graphene coated fabrics for hydrophobic applications, focusing on graphene incorporation into fibers and its uses. We consider publications from 2018 to 2023.

Received on 17 September 2023; revised 15 December 2023.
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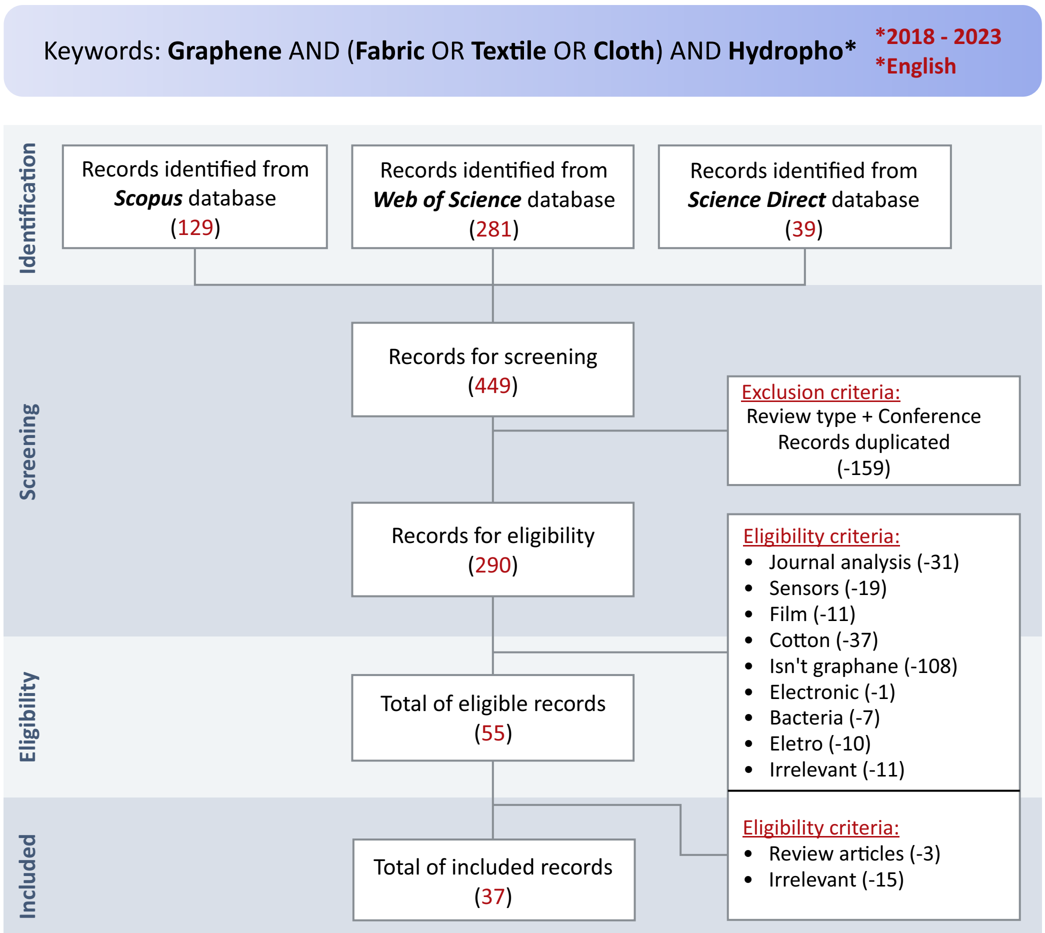
J Bioeng. Tech. Health 2024;7(1):87-92

Materials and Methods

In this study, we performed a systematic review using the PRISMA method [10]. We searched Scopus, Web of Science, and Science Direct for articles in English published between 2018 and 2023, using keywords like graphene, fabric, textile, cloth, and hydrophobic. lnitially, we found 449 studies. Two reviewers independently assessed the relevance of titles and abstracts, excluding conference papers, review studies, and duplicates (159), resulting in 290 studies for further analysis. Figure 1 depicts the study selection process following PRISMA guidelines.

After the initial selection, exclusion criteria were applied based on the absence of graphene impregnation (108), studies related to sensors (19), films (11), electronics (1), biological applications (7), and electronic devices (10), resulting in a total of 55 studies deemed relevant to the subject under analysis. The identified articles underwent independent evaluation of their titles and abstracts to assess their suitability, leading to a total of 37 articles that were included in this study.

Figure 1. Systematic review flowchart according to the PRISMA protocol.



Results and Discussion

Figure 2 presents a graph containing data obtained through the PRISMA protocol, showing an increase in studies related to fabrics coated with graphene over the last five years. Until this research, when the data was compiled, there were already 3 articles in this area, and more studies are expected. The highest number of studies was recorded in the years 2019 and 2022. ln 2019, there was an increase of approximately 122% compared to the previous year, while in the period from 2020 to 2021, the number of registrations remained the same as in 2018. The most significant increase in registrations was identified in 2022, with a 155% increase compared to 2018, 2020, and 2021.

The systematic review focused on evaluating graphene synthesis methods, particularly emphasizing the chemical reduction of graphene oxide (GO) for fabric applications. Among the reviewed studies, GO was prevalent, featuring 25 studies related to hydrophobic fabrics, while other types of graphene (sheets, reduced, and quantum) were identified in 12 studies. GO is distinguished by its numerous oxygen-based functional groups on its surface, providing active sites for chemical functionalization and developing specific properties. The synthesis of GO can be achieved through three primary methods: Brodie's, Staudenmaier's, and Hummer's methods, with the latter being the most frequently cited in this study [2,4,13-18]. The studies were further categorized

Figure 2. Studies published in this systematic review by (a) year since 2018, (b) year since 2008, and (e) by graphene type.

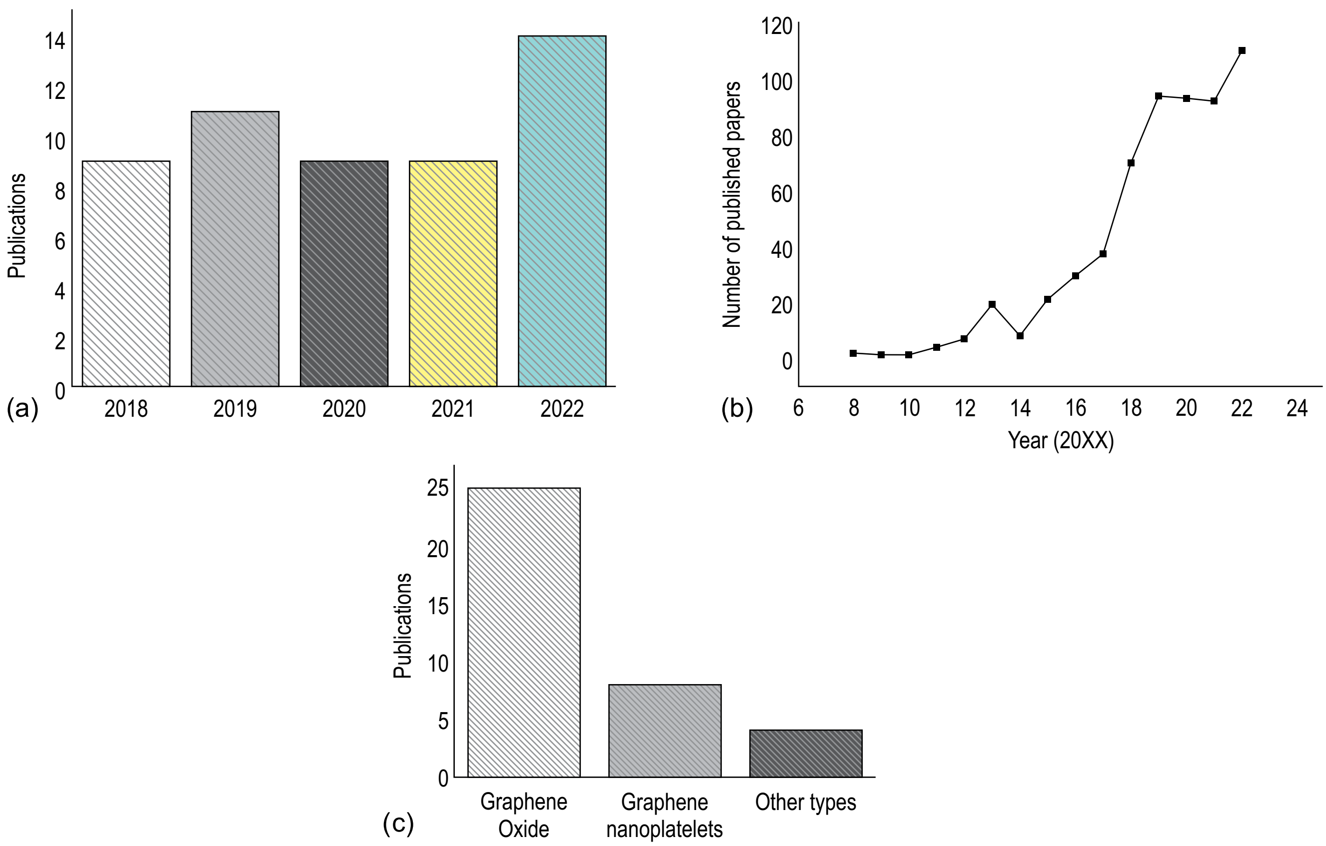
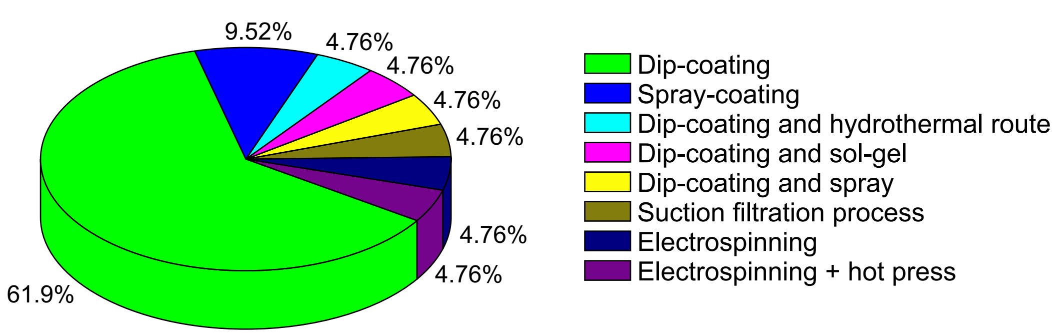


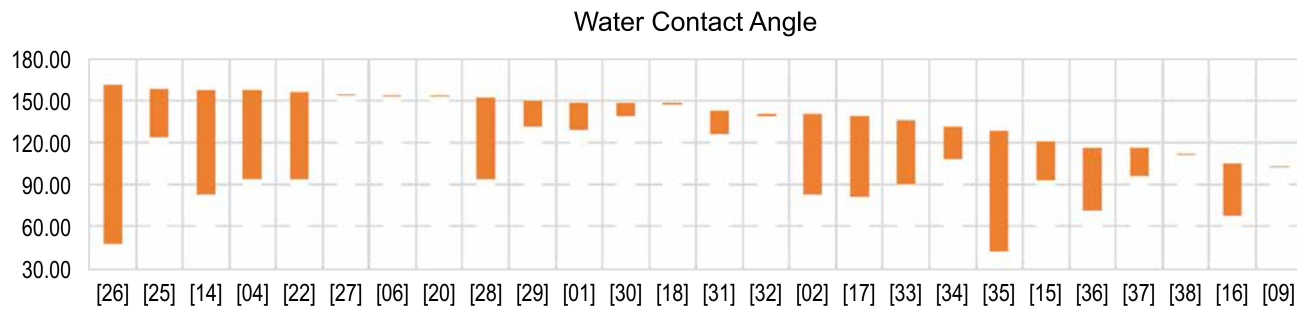
Figure 3. Studies published in this systematic review by application method.



based on the method of graphene application onto the fabric surface, with the dip-coating technique emerging as the most commonly mentioned (15 studies) due to its efficacy in achieving aligned and layered structures for high-quality coatings (Figure 4).

Dip-coating is a widely utilized process for dyeing, printing, or applying various chemical finishes to textile materials such as fabrics, knits, yarns, and nonwovens. This technique has gained prominence in fabric applications owing to its simplicity, strong adhesion, easy availability, and potential for large-scale production [1,5,6,19-23]. Fang and colleagues (2019) studied the preparation of glass fibers coated with graphene and high electrical conductivity through the sol-gel and dip-

Figure 4. Studies published in this systematic review by water contact angle.



coating techniques, and they reported that the dip-coating method achieved the best properties [16].

The studies included in this systematic review employed various analyses, such as scanning electron microscopy (SEM), thermogravimetry (TGA), Fourier-transform infrared spectroscopy (FTIR), dynamic mechanical analysis (DMA), X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS), to evaluate the efficiency of graphene incorporation into the fabric's structure. However, these studies' primary property and objective were hydrophobicity. The "Lotus Effect," described by Oles and colleagues (2000), refers to the physical properties that characterize a superhydrophobic and self-cleaning surface. This property is typically assessed through contact angle analysis, where a contact angle less than 90º indicates a hydrophilic surface, meaning the liquid can wet it. Conversely, a contact angle greater than 90º indicates a hydrophobic surface, with a contact angle exceeding 150º termed superhydrophobic. In this systematic review, 35 studies evaluated hydrophobicity through contact angle measurements. Figure 5 illustrates the relationship between the highest contact angle values achieved after the incorporation or coating of the fabric with graphene.

Out of the total of 35 studies that evaluated the contact angle of the fabric after graphene modification, 28 studies successfully modified the fabric surface to achieve a hydrophobic classification [1,2,3,6,9,14-18,20,22,25-38].

Various resin matrices, including PET, PU, PP, and polyester, were examined in multiple studies. The focus was on functionalizing graphene, not resin synthesis. For instance, Achagri and colleagues (2020) achieved a 148º contact angle on PET fabric using dip-coating [1]. Atighi and colleagues (2022) and Wang and colleagues (2018) also obtained contact angles exceeding 100º for PET matrices. PET exhibits partial hydrophilic properties due to its oxygen-containing groups, resulting in a 71.4º contact angle. Coating with graphene oxide increased the angle to 116.3º [36].

Among the studies in this review (37), 65% focused on developing fabrics for oil-water separation applications. Other applications included flame retardancy [38], catalytic activity [21], self-cleaning [4], and anticorrosive coatings [26,28,39].

Conclusion

The systematic review presented in this article provides a comprehensive overview of recent studies focused on fabric modification with graphene for hydrophobic applications. The reviewed works demonstrate a significant enhancement in fabric hydrophobicity following graphene modification in various forms. Dip-coating emerged as the predominant and favored approach among the different application methodologies explored in the reviewed studies.

Notably, graphene oxide was found to be the most commonly utilized variant of graphene, significantly surpassing other graphene forms in frequency of usage.

The integration of the dip-coating technique with graphene oxide infusion was of particular significance. This combined approach resulted in a consistent and notable improvement in hydrophobic properties across the reviewed studies. The synergistic effects of dip-coating and graphene oxide infusion consistently yielded superior results, substantially enhancing the materials' ability to resist wetting and repel water.

Acknowledgments

The authors thank the TRL9 TECH Company and Brazilian Research Agency-CNPq for all the technical and financial support.

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