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Recent Progress to Address the Challenges of Conductive Inks for E-Textiles †

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Abstract: Fabricating printed electronic inks that are highly stable on textile substrates has remained a challenge for researchers to fully achieve e-textiles for various sensing and health monitoring applications. This review reports progress in addressing challenges with conductive inks for e-textiles. Relevant studies highlight major achievements including developing stable carbon nanotube and graphene inks with consistent electrical properties, formulating silver nanowire inks with excellent conductivity and flexibility, and enhancing the adhesion of carbon nanotube inks to fabrics without pretreatment. Key findings show improved dispersion and biocompatibility of carbon nanotubes using silk protein, high stability of graphene inks in optimized solvents, and flexible semiconductor inks able to withstand bending. Overall, advances have expanded the capabilities of e-textile devices fabricated with conductive inks.

Keywords: conductive inks; fabrication challenges; conductivity performance

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1. Introduction

Conductive-inks are critical components in the development of e-textiles, with the potential to transform the textile industry by enabling the production of smart fabrics that can feel, react, and communicate. However, the development of conductive inks for e-textiles has been hampered by a number of issues, including poor adhesion, thermal stability, and mechanical stability. The goal of this study is to highlight the common challenges, identify recent advances in tackling these difficulties, and to suggest potential solutions. This discovery is significant because of its potential to speed the development of e-textiles and enable the development of new applications in domains such as healthcare, sports, communication, and fashion.

2. Methodology

To understand the recent progress, relevant keywords, or search blocks were used to search for publications from the Scopus database. Here, the search block ("printed electronics" OR "metal inks" OR "conductive inks" AND "problems" OR "challenges" AND "textiles") was used to identify articles and conference papers published within the subject area. The identified publications were analysed, and a brief summary of the findings is provided in the next section.

3. Results and Discussion

Fabricating highly conductive inks on textile substrates has remained a challenge for researchers to fully achieve e-textiles for various sensing and health monitoring applications. These conductive inks tend to replace the conventional rigid material electrodes for wearable technologies. However, compounds that formulate these inks present setbacks including crystallinity (film morphology) and non-biocompatibility.

In this review paper, a summary of relevant studies selected from the Scopus database revealed that deformation and transiency from mechanical bending and washing affect the electrical conductivity of conductive inks [1,2]; poor adhesion between the inks and the uneven surface or fibrous nature of the textile substrates affects the conductivity performance [3]; ink diffusion is formed based on the fibrous, porous nature of the textile and the viscose nature of conductive inks [4]; and the crystallinity poor or uneven formation of conductive layers on textiles are formed due to the porous and roughness nature of the substrate [5–7]. Inorganic compounds in conductive inks show severe cytotoxicity, which tends to limit their application in biosystems [8]. A hybrid ink composed of natural Silk Sericin and CNTs is biocompatible; formulated graphene-based (graphene nanoplatelets) conductive inks composed of organic compounds successfully responded to the consistency in electrical properties over a storage period of two months and are suitable in the development of wearable electronics [9]. Due to the poor adhesion and low electrical conductivity of the porous and rough nature of the fabric surface, there was a formulation of curable silver nano-conductive ink, which is preferable for micrometre-level pore-size carbonate-coated nylon woven fabric that assumes good adhesion and excellent continuous electrical conduction [5]. Another study conducted by [6] fabricated a UV curable nano-silver conductive ink, a low-cost and environmentally friendly method that cures quickly at a lower temperature for fabrics. The experimental process aimed at tackling the issues of poor adhesion and low electrical conductivity caused by the porous structure and rough surface of fabric substrates. In a study conducted by [5], a thermoplastic polyurethane (TPU)-based multi-walled carbon nanotube (TMWCNT) conductive ink was fabricated, suitable for the production of screen-printed fabric electrodes (SPFEs) with excellent conductive and mechanical performance. Good interfacial adhesion between TMWCNT conductive ink and polyamide fabric was also demonstrated in the cross-sectional picture of the FE, which showed no obvious delamination of the conductive TMWCNT layer from the fabric substrate.

Evidently, e-textiles are produced via numerous approaches including knitting and crocheting, weaving, braiding, coating or laminating, chemical processing, and printing [10]. In the creation of flexible circuits on fabrics, conductive inks play a crucial role in printing (inkjet, screen, gravure, lithography), providing avenues for customization, scalability, and affordability in product manufacturing [11]. For example, screen printing was used to create silver nanowires with dimensions of 60–100 nm in diameter for two 0.06 W LEDs and 1 K resistor circuit diagram on a clean woven fabric in lighting LEDs properly with AgNW ink [12]. With other techniques like ultrasonic spray coating, conductive metals are deposited on flexible materials at low temperature [13]. Through digital printing, scalable solid-state microchips of flexibility were integrated into prints via pol-gel, which undergo transition upon exposure to solvent vapour [14].

The *syringe-based deposition system* was experimented by [15] which showed the capability of printing and further curing of the micro-conductive ink on fabric substrates. Via other printing techniques like the *direct-write printing* approach, metasurfaces were printed on two different nylon fabrics coated with polyurethane on the reverse side for mechanical reinforcement and to prevent the ink from bleeding through to the other side [16]. The success of these techniques paved ways for further experimentation to fully integrate conductive inks on the textile substrate for effective performance and functionality.

Based on the findings, the study proposed some technical solutions for an effective fabrication of conductive inks to overcome the identified challenges. These include surface pretreatment using plasma techniques to improve the adhesion or binding of the conductive inks and the textile substrate; the fabrication of conductive inks using nano-size particles to enhance ink-penetration and encapsulating with protective coating for stability and deformation resistance; and the optimization of conductive inks using non-toxic or environmentally friendly solvents. Others are, the fabrication of conductive ink on elastomeric materials for stretchable fibres/fabrics which would improve mechanical stability and experimenting with different curing techniques like electron beam curing, UV light, and heat which could help improve poor thermal stability.

4. Conclusions

This review paper highlights the critical challenges, i.e., poor adhesion, ink diffusion, uneven formation of conductive layers, deformation, and transiency, encountered within the field. Relevant studies outlined in this work adopted novel approaches, i.e., composition materials for conductive inks and deposition techniques to overcome some critical challenges affecting the full realization of printing conductive inks for e-textiles. By developing appropriate composition materials and using alternative curing techniques like UV and heat curing, amongst others, these challenges can be resolved to promote large-scale production. Future studies should investigate optimizing techniques for deposition of synthesized conductive inks for printing on textile substrates. This success will improve the quest to the large scale production of conductive inks on the fabric substrates for e-textiles.

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