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NANOPARTICLES IN SPORTS GARMENTS: A REVIEW STUDY[1]

NANOPARTÍCULAS EM VESTUÁRIO ESPORTIVO: UM ESTUDO DE REVISÃO

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ABSTRACT

The present study aims to carry out a lifting, analysis, and description of scientific publications such as articles on nanoparticles in sportswear with the focus on heat control, odor, electricity generation and bacterial infections. Thus, an exploratory search was realized in the *ScienceDirect* and *Scopus* from 2019 to Sep 2023. In relation to the production of nanoparticles and fabric, the nanocoating technique is used and can be applied directly to the fabric fiber or with application in the form of a spray on the item of clothing. The application/combination of nanomaterials such as titanium dioxide (TiO_2-NPs), silver nanoparticles (Ag-NPs), zinc oxide nanoparticles (ZnO-NPs), and polymer fibers (cellulose diacetate, bacterial cellulose, and polytetrafluoroethylene) allow properties such as antibacterial activity, solar protection and superhydrophobicity to provide breathability, aesthetics, flexibility, and the ability to not cause allergic reactions compared to cotton fabric generally relating the main mechanism to the generation of free radicals and high electronic conductivity.

Keywords: Metallic nanoparticles, nanotechnology, sports, tissue.

RESUMO

O presente estudo tem como objetivo realizar um levantamento, análise e descrição de publicações científicas como artigos sobre nanopartículas em roupas esportivas, com foco em controle de calor, odor, geração de eletricidade e infecções bacterianas. Deste modo, foi realizado uma busca exploratória na base de dados ScienceDirect e Scopus de 2019-set 2023. Em relação a produção de nanopartículas e tecido, utiliza-se a técnica o nanocoating (nanorevestimento) e pode ser aplicada diretamente na fibra dos tecidos ou com aplicação em forma de spray sobre a peça de roupa. Com isso, a aplicação/combinação de nanamateriais como o dióxido de titânio (TiO_2-NPs), nanopartículas de prata (Ag-NPs), nanopartículas de óxido de zinco (ZnO-NPs) e fibras de polímeros (diacetato de celulose, celulose bacteriana e politetrafluoretileno) permitem que propriedades como atividade antibacteriana, proteção solar e superhidrofobicidade possibilitam a respirabilidade, estética,

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flexibilidade e capacidade de não provocar reações alérgicas comparado com tecido de algodão geralmente relacionando o principal mecanismo como geração de radicais livres e elevada condutividade eletrônica.

Palavras-chave: *Nanopartículas metálicas, nanotecnologia, esportiva, tecidos.*

INTRODUCTION

Body temperature regulation is an essential function for endothermic living beings, such as in humans generally at around 36.5 at 37.5 °C (Geneva *et al.,* 2019; Saper; Machado, 2020). In this way, thermal comfort is generally achieved through two methods (Zhao *et al.,* 2021): (a) the use of air conditioning and (b) the use of clothing that regulates body temperature in external environments. It is worth mentioning that common clothing made with natural or synthetic fibers has limited thermal performance, as these fibers are relatively large, making air circulation and thermal insulation difficult (Carleton; Hsiang, 2016).

At the same time, healthcare-associated infections (HAIs) caused by pathogens, such as bacteria and viruses, are a serious problem that affects both society and the economy. In recent years, the textile industry has focused on developing fabrics with functional properties. Therefore, polyester fibers are widely used in the manufacture of clothing and industrial products, due to their high modulus of elasticity and good resistance to heat and chemicals (Ürge-Vorsatz *et al.,* 2012; Cabeza; Gracia, 2021).

However, the lack of hydrophilic groups in the polyester composition results in low moisture absorption. Furthermore, the high degree of crystallinity and orientation of polyester fibers promotes a densified structure, reducing moisture permeability (Wang *et al.,* 2018). It is worth mentioning that polyester fibers have difficulty dissipating perspiration, which can cause a feeling of stuffiness and discomfort, causing discomfort, requiring the use of nanotechnological products, in order to promote greater comfort and applicability (Abdelgawad *et al.,* 2020; Fouda *et al.,* 2020).

Nanotechnology is an area that has revolutionized several sectors, such as the sportswear industry. The incorporation of metallic nanoparticles in sports fabrics has provided significant advances, mainly to promote comfort and improve the performance of athletes (Mediene; Senoudi, 2023). For example, mesoporous silica nanoparticles (MSNs) have been used in nanotechnology fabrics for antiperspirant and deodorant properties, as well as antibacterial performance (Hassabo *et al.,* 2015; Hassabo; Mohamed, 2019). Conductive fabrics can be produced by mixing metallic threads with fabric fibers or functionalizing fabrics with a film of conductive materials, ensuring greater comfort and resilience, air permeability and waterproofing (Mazroua *et al.,* 2019).

In view of the above, the development of efficient antimicrobial agents and temperature regulators is encouraged, such as metallic nanoparticles (MNPs) with optical activity, capable of generating reactive oxygen species, optimizing applications. Titanium and silver nanoparticles (TiNPs and AgNPs) have been shown to be one of the promising candidates for combating various bacterial infections, when synthesized from biogenic synthesis, that is, using plant extracts rich in flavonoids as a reducing agent for metal ions in solution (Ti^{4+}) (Yin *et al.,* 2020; Nirmala; Bajwa; Oinam, 2024). Copper oxide nanoparticles (CuO-NPs) are a strongly attractive p-type semiconductor to be used in degradation processes and body regulation, especially due to their narrow band gap energy (Eg ~ 1.25-1. 75 eV), low toxicity and cost-effectiveness when obtained by biogenic synthesis (Yin *et al.,* 2022). It is worth noting that the parameters of particle size, elemental composition, encapsulation affect functionality.

In this context, the present review study aims to identify the main metallic nanoparticles used in sports clothing, relating applications involving antibacterial activity, heat exchange, humidity, hydrophobicity, and electrical and thermal conductivity. The novelty of this review is to describe the main nanoparticles for the application of nanotechnological fabrics.

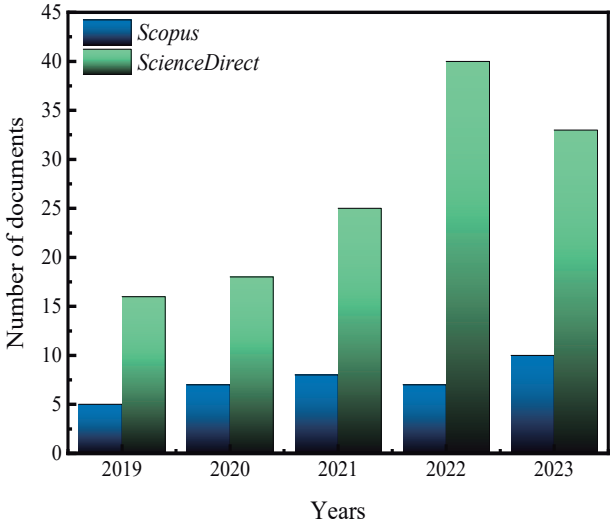
METHODOLOGY

This review study was carried out in an integrative literature format, being qualitative and exploratory, through the analysis of scientific articles on the *ScienceDirect* (https://www.sciencedirect.com) and *Scopus* (https://www.scopus) platforms. com), following Boolean logic, from 2019 to September 2023. Furthermore, the words ‘nanoparticles’ and ‘sports clothing’ and their respective English descriptors ‘nanoparticles’ and ‘sports clothing’ were used. All studies analyzed were those that presented the described theme and in association with processes involving metallic nanoparticles, aiming to analyze the main applications (such as antibacterial, hydrophobicity and heat resistance) and parameters that directly affect the nanoparticles.

RESULTS AND DISCUSSION

Figure 1 presents the articles found on the *ScienceDirect* and *Scopus* platforms from 2019 to September 2023.

Figura 1 - Scientific articles published per year in the *ScienceDirect* and *Scopus* databases between 2019 and Sep/2023.



Source: author

According to Figure 1, 132 and 37 scientific articles were found in the ScienceDirect and Scopus.com databases, respectively. In short, the topic of sportswear containing nanomaterials demonstrates a growing trend of published articles correlating different sizes, properties and applications possibly due to new research involving antibacterial applications, contact surface, resistance to heat and cold and comfortability. Furthermore, the increase in the number of articles occurs on both platforms with the first articles published showing a percentage increase of articles on ScienceDirect of 221%, denoting a current, important, and relevant topic. It is worth mentioning that the differences found in the databases may be due to the number of journals associated with each database (Scopus and ScienceDirect). Table 1 presents the results found for sports fabrics, applications and main properties of the nanoparticles used from the ScienceDirect and Scopus platforms (2019-Sep/2023).

Table 1 - Results found for sportswear containing nanoparticles on the *ScienceDirect* and *Scopus* platforms (2019-Sep/2023).

Nanoparticles	Application	Properties	Reference
CA-BIC	Fabrics resistant to extreme environments	k = 27.2-28.4 mW m^{-1} K^{-1}, P_p = 99.25-99.36%, and Θ = 162°	Yin *et al.,* 2022
ZnO-NPs@SiO_2h	Antibacterial fabrics	MIC = 2.73 x 10^6 cells mL^{-1}, and Θ = 155°	Kim *et al.,* 2021
PPy@TiO_2-NPs	Multifunctional, and durable fabrics	σ = 10^{-14} S cm^{-1}, and P_s = 74 nm	Mohamed *et al.,* 2021
PTFEf	Fabrics integrated with wearable electronics	ε = 11.0%, and Ab_s = 83.7%	Zhang, Y. *et al.,* 2022
Pal-PDA@PET	Fabrics for less perspiration	Θ = 9.46°, and ΔHe = 1429 J g^{-1}	Zhang, X. *et al.,* 2022
CelB@$CoFe_2O_4$	Fabrics with flexible electromagnetic sensors	Bio = 100% (56 h), and R_r = 37.13 MPa	Chen *et al.,* 2022

AuNPs-c	Antibacterial fabrics	MIC = gram-positive bacteria (≥ 98.5%), and MIC = gram-negative bacteria (≥ 99.94%)	Zhu *et al.,* 2022
AgNPs@TMSPM	Hydrophobic cotton fabrics	Θ = 148.3°	Pal *et al.,* 2022

CA: cellulose diacetate hybrid nanofibers, BIC: isocyanate crosslinker, k = thermal conductivity, P_p = porosity, Θ = contact angle, ZnO-NPs = zinc oxide nanoparticles, SiO_2h = hydrophobic silicon dioxide, MIC = minimal concentratory inhibition, PPy: polypyrrole, TiO_2-NPs = titanium dioxide nanoparticles, σ = electric conductivity, P_s = particle size, PTFEf = polytetrafluoroethylene nanofiber membrane, ε = thermal emissivity, Ab_s = maximum solar absorptivity, Pal = palygorskite, PDA = polydopamine membrane, PET = polyester fabric, ΔH_e = enthalpy evaporation, CelB = bacterial cellulose, $CoFe_2O_4$ = cobalt ferrite, Bio = biodegradability, R_r = breaking strength, AuNPs-c = gold nanoclusters, AgNPs = silver nanoparticles, and TMSPM = fluorine-free silane and 3-(trimethoxysilyl methacrylate).

The waterproof cellulose diacetate nanofiber (CA-BIC) aerogels with good breathability and moisture permeability were produced from the impregnation method, where the formation of a hierarchy of lamellar structure was adjusted to increase the mechanical properties such as compressive stress (90%) and elasticity (withstands 20,000 cycles) at ultra-low temperatures (-196 °C). Thus, the thermal conductivity found to be 27.2-28.4 mW m^{-1} K^{-1} was higher than cotton fabrics, suggesting a potential material for heat retention (Yin *et al.,* 2022).

Zinc nanoparticles (ZnO-NPs) electrostatically deposited on fabrics can simultaneously reduce droplet adhesion (Θ = 155°) and bacteria viability, effectively decreasing the risk of bacterial infection possibly due to EPD processes. In this way, porous nanoparticles use electric fields on substrates (SiO_2h) to control the amount of layer deposition independently without harming both properties (antibacterial and anti-humectant) (Kim *et al.,* 2021).

Multifunctional textiles that acquire more than one property have lately gained more interest like PPy. Titanium nanoparticles (TiO_2-NPs) demonstrated high electrical conductivity (10-14 S cm^{-1}) inhibiting the prevalence and occurrence of infections due to the decrease in particle size (± 74 nm) resulting in an increase in affinity for the chains cellulosic materials remaining hygienic and odor-free even after 20 washing cycles and can be used in biosensors and electromagnetic shielding (Mohamed *et al.,* 2021).

Clothing integrated with wearable electronics is divided into 2 basic functions: thermal management and electricity generation. PTFEf denotes a minimum thermal emissivity of up to 11.0% and a maximum solar absorptivity of up to 83.7% allowing a 3 °C drop in the internal heating of the fabric compared to cotton saving 25.2-100% of consumption of building energy in ten cities around the world. In this way, it produces solar and passive energy, radiative heating, but also collects biomechanical energy to generate electricity (Zhang *et al.,* 2022).

Polyester fabric (PET) is one of the most used clothing fabrics in everyday life; however, PET's sweat management is extremely poor. The combination of Pal-PDA@PET increased the number of hydrogen bonds resulting in excellent moisture management properties, low energy consumption and environmental protection for industrial applications, due to increased hydrophilicity (Θ = 9.46°), lipophilicity, moisture absorption, light-to-heat conversion performance, evaporation rate (ΔHe = 1429 J g^{-1}) and tensile strength (Zhang *et al.,* 2022).

Flexible electromagnetic sensors on composite-based fabrics were tested on a customized test platform, manifesting excellent sensing properties and stability. CelB@$CoFe_2O_4$ showed 100% fabric biodegradability (in 56 hours) and Rr of 37.13 MPa, due to the combination of cellulose fibers with Co^{2+} and Fe^{2+} ions. In this way, being able to monitor motion signals and distinguish the motion state, proving that the biodegradable flexible electromagnetic sensor is promising used in the wearable field as a kind of environmentally friendly flexible sensor (Chen *et al.,* 2022).

Designing long-lasting, high-efficiency antimicrobial and deodorant fabrics is an eternal goal for environmental and public health. Thus, gold nanoclusters (AuNPs-c) showed antibacterial activities against gram-positive (≥ 98.5%) and gram-negative (≥ 99.94%) bacteria, due to the intriguing characteristics of Au^+ ions having photodynamic production. of reactive oxygen species in visible light and the rich surface chemistry, allowing the inhibitory effect on bacteria and denoting biocompatibility in fibroblast cells (Zhu *et al.,* 2022).

The anti-wetting properties, surface morphology, chemical composition and functionality of hydrophobic cotton fabrics are important for today's clothing. Therefore, the superhydrophobic surface (Θ = 148.3°) of AgNPs@TMSPM is due to the high (> 90%) crystalline nature of AgNPs and modification of methacrylate groups in the silane conferring multifunctional properties (Pal *et al.,* 2022).

Therefore, the use of nanoparticles in sports apparel is a promising area of research, with the potential to improve athletes' performance and reduce the risk of injury. However, there are still some difficulties that need to be overcome for this technology to become widely used, such as costs, as nanoparticles are generally more expensive than conventional materials and safety, nanoparticles can be toxic if not properly used and it is necessary to see the influence on performance (Zhang *et al.,* 2023).

CONCLUSION

In the respective work, it was possible to carry out a survey and description of scientific articles on nanoparticles in sports clothing with a focus on heat, odor control, electricity generation and bacterial infections applications. The qualitative and exploratory integrative search in the *ScienceDirect* and *Scopus* databases from 2019-Sep 2023 showed an increase of 221% denoting a current, important and relevant topic. Applications of nanoparticles titanium, silver, gold, zinc and nanofibers (cellulose diacetate and polytetrafluoroethylene) in fabrics (generally cotton) increase thermal and electrical properties (conductivity), antibacterial activity (due to inhibition by reactive oxygen species), protection UV-Vis and superhydrophobicity (interaction of atoms with the environment), due to the smaller particle size and interaction with the substrate, enabling better breathability, aesthetics, flexibility and the ability to not cause allergic reactions. Therefore, the theme of sports fabrics involving nanotechnology denotes an exponential increase over the years with excellent properties.

However, there is a lack of data on the issue of nanoparticle toxicity (biocompatibility) which must be studied, explained, and highlighted.

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