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Mechanism and Implications of Nanoparticle Release from Commercial Nano-Textiles: A systematic review

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ABSTRACT

The application of nanomaterials in textiles is a result of the growing consumer desire for robust, environmentally responsible apparel. Concerns are raised, meanwhile, regarding the effects of engineered nanomaterials (ENMs). Research has looked into the release of nanoparticles from fabrics during washing and use. However, the available studies vary widely, making a thorough understanding difficult. To compile the available data and provide a comprehensive analysis of nanoparticle release from commercially used and washed nano-enhanced textiles, a systematic review is necessary. We used PRISMA guidelines to search for the available literature using pre-specified inclusion and exclusion criteria. These databases provided 1158 relevant research articles, which Endnote software screened for duplicates. 36 studies were considered relevant for reading in full after 479 distinct abstracts were assessed for relevant studies. After complete text evaluation, only 13 of these articles were found to be relevant. New Castle Ottawa (NOS) was used for the risk bias assessment of all included studies. The findings show that a significant quantity of nanoparticles can be released by textiles using nanotechnology. Numerous factors, including the structure of the nanoparticles, the adhesive qualities, the type of fabric, and the interactions with the environment, affect the characteristics of those released particles, particularly their quantity and composition. These findings highlight potential risks associated with nanoparticle release, highlighting the need for toxicological evaluations and further research into particle behavior, with a focus on the functional aspects of fibers and how they affect the environment after nanoparticle release after washing, even though there are differences between laboratory simulations and real-world conditions.

Keywords: Nano-textiles, Nanoparticles, Silver nanoparticles, engineered nanomaterials

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1. INTRODUCTION

Advancements in technology have transformed the world. The development of nanotechnology pushed mesoscopic physics to the forefront. Nanotechnology includes both nanotechnology and Nanoengineering (Beigzadeh et al., 2024). The scientific fields of nanotechnology, Nanoscience, and Nanoengineering have enormous potential for changing possible applications to a surprising extent (Hassan et al., 2019).

In science, nanomaterials represent small units of molecules that make up atomic and molecular structures. The fields of microbiology, optical technology, electronics, textiles, health care, coatings, the aerospace industry, materials science, energy, materials for plastics, and mechanics are just a few of the seemingly endless applications that nanoparticles, Nanofluids, nanowires, and Nanofilms may contribute (Temesgen et al., 2018). In addition to their high surface area, conventional materials that have been impregnated with nanoparticles have beneficial properties. As one moves from the microscopic to the nanoscopic level, it is apparent that certain characteristics change. As an example, while ceramics are highly valuable materials, their brittleness limits their applications because it reduces grain size to the nanoscale, making them malleable (Vílchez et al., 2016). Nanoparticles retain different characteristics by precise and controlled configurations of molecules and atoms. Since bottom-up technology produces high-quality materials with fewer flaws, nanotechnology-based materials are superior. Bottom-up technology states that larger constructions can be reduced in size and expense by using fewer resources (Lorenz et al., 2012).

The textile sector has been grasped by nanotechnology as it has improved the material's water resistance, antibacterial properties, and durability (Som and Gallen, 2007). Commercial nano-textiles with improved performances over conventional materials have been made possible by the incorporation of nanoparticles into fabrics. These textiles have advantages over regular clothing in the medical textile industry because they contain nanoparticles of metals including titanium, zinc, and silver (Joshi, 2008). However, using nanoparticles in textiles raises several questions regarding their potential to leak out during routine washing, use, or disposal, which could have negative effects on the environment and human health (Ramos and Almeida, 2017). With the increasing application of nano-textiles, the behavior of nanoparticle release has emerged as the main subject of study. Such mechanisms depend on variables like the nature of nanoparticles, how nanoparticles are incorporated into textiles, and the conditions in which it is used (Rivero et al., 2015). Some layers may be released through wear and tear, mechanical stress during washing, or contact with water and chemicals. These particles make textile properties optimal, however, if they are emitted accidentally they can detrimentally impact the environment and if they get into the life cycle or touch the human skin, they will have a negative impact on human health (Tarafder, 2018).

The available literature at the present time has identified specific shortcomings in our knowledge about the degree and characteristics of nanoparticle emissions from ready-to-wear

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fabrics. It has therefore been deemed necessary to critically address the body of research work based on the factors that may lead to release, estimate the amount of release depending on the circumstances, and appraise the dangers likely to be occasioned by extended exposure to these nanoparticles. This review is intended to discuss how nanoparticles are released, what particle structures are used, and various environmental and public health consequences while presenting an overview of existing knowledge on this continually advancing subject.

2. METHODOLOGY

This systematic review of available studies on our topic was conducted according to the PRISMA guidelines ("Preferred Reporting Items for Systemic Reviews and Meta-Analyses") (Moher et al., 2010).

Search strategy

We use five different databases for searching published studies in English without the publishing timeframe restriction. The following search strategy were used for each database: **Scopus:** (TITLE-ABS-KEY("nanoparticle release" OR "nanomaterial release") AND TITLE-ABS-KEY("nano-textiles" OR "nano fabrics" OR "nanotechnology textiles" OR "nanoparticle coated textiles") AND TITLE-ABS-KEY("mechanisms" OR "abrasion" OR "washing" OR "leaching" OR "degradation") AND TITLE-ABS-KEY("environmental impact" OR "health risks" OR "toxicity" OR "exposure")), **Web of Science:** TS=("nanoparticle release" OR "nanomaterial release") AND TS=("nano-textiles" OR "nano fabrics" OR "nanotechnology textiles") AND TS=("mechanism" OR "release mechanism" OR "abrasion" OR "washing" OR "leaching") AND TS=("environmental implications" OR "health impact" OR "toxicity" OR "exposure"), **PubMed/EMBASE:** ("nanoparticle release" OR "nanomaterial release") AND ("nano-textiles" OR "nanotechnology textiles" OR "nanoparticle-coated textiles") AND ("release mechanisms" OR "abrasion" OR "washing" OR "leaching") AND ("environmental impact" OR "health risks" OR "toxicity" OR "exposure"), **Google Scholar:** "nanoparticle release" AND "nano-textiles" OR "nanotechnology textiles" AND "mechanism" OR "abrasion" OR "washing" AND "environmental impact" OR "toxicity", and **Cochrane Library:** ("nanoparticle release" OR "nanomaterial release") AND ("nano-textiles" OR "nanotechnology textiles") AND ("release mechanism" OR "abrasion" OR "leaching") AND ("environmental implications" OR "toxicity"). We also checked these databases for the presence of previous or ongoing systematic reviews on the subject. We combined results from different databases and discarded repeated results using Endnote software.

Studies Selection

All articles were extracted and stored in a separate Endnote Library (ENDNOTE, 2015) and duplicates were removed. Studies were selected for inclusion by two different reviewers.

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Reviewer 1 evaluated titles and abstracts in duplicate, separately, while reviewer 2 approved studies based on the data and solved any disagreements on any included study. After the papers were thoroughly reviewed by reviewers, they were selected for inclusion based on the subsequent inclusion and exclusion criteria, which helped establish if the publications contained the necessary data for the systematic review:

Inclusion Criteria

- Randomized control trials, Cohort studies, and prospective studies were included in this review.
- Studies that examine the mechanisms of nanoparticle release (e.g., abrasion, washing, UV exposure).
- Studies involving commercial nano-textiles embedded or coated with nanoparticles (e.g., silver, titanium dioxide, zinc oxide).
- Studies that were published in the English language

Exclusion criteria

- Studies that were case reports, systematic reviews, editorial letters, non-comparative studies, and case series were excluded
- Studies focused on non-commercial nano-textiles or experimental prototypes not relevant to real-world applications.
- Studies focusing on non-nanoparticle-based textiles or materials that do not use engineered nanoparticles (e.g., bulk metal coatings, organic dyes).
- Studies published in languages other than English

A Microsoft® Excel Spreadsheet was used to extract and store data and records (Microsoft, Inc., Redmond, Wash., USA).

Risk Bias Assessment

The Newcastle Ottawa Scale (NOS) was used to assess the included studies. Studies were scored low, medium, and high based on bias in the selection, bias in interventions, bias in deviations interventions, bias because of data missing, bias in outcomes, and bias in results. Inclusion and exclusion criteria were used for scoring of preference for selection. Performance bias was assessed by accounting for allocation concealment and describing a control arm. Various rankings were given to incomplete industry sponsorship, data management, biased reporting, and selective reporting. Reporting uniformity and eligibility limitations were discussed over several meetings with reviewers. Before choosing a study, a second reviewer took into account any gaps in the reviewers' scoring.

The evidence's quality and certainty were evaluated using GRADE (Grading of Recommendations Assessment, Development, and Evaluation). Regarding quality and

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certainty, the evidence is categorized as high, moderate, or low. The uncertainty of the evidence (the outcome measure's lack of direct relevance to the purpose of the study), imprecision of the results, the seriousness of inconsistent results, the designs of the included studies, the seriousness of the risk of bias, and other factors like publication bias are all taken into consideration by the GRADE system when evaluating the quality and certainty of included studies.

3. RESULTS

Search results

A total of 1158 studies were found on five different databases. When the studies were sorted on Endnote, 679 studies were excluded as duplicates. 479 studies were screened based on titles and accessibility. Among them, 443 studies were excluded as only the abstract was accessible. 36 full article texts were retrieved and assessed for eligibility in which only 23 studies were found to be eligible for our studies. When these articles were carefully studied, 12 articles were excluded because of lack of investigation of nanoparticle release, which was irrelevant and was excluded from the study. The studies were shortened to just 11 studies, which we included in this systematic review **(Figure 1)**.

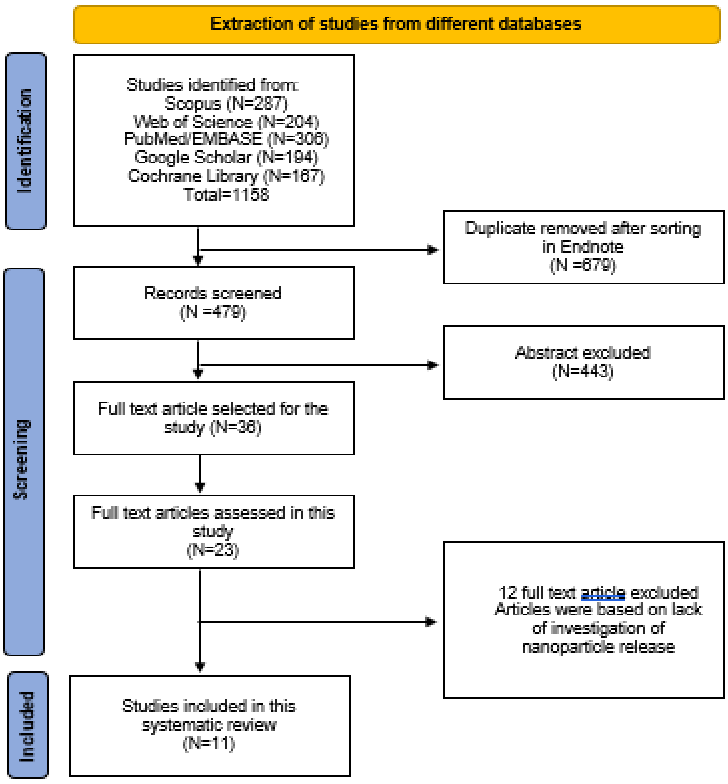

Figure 1: PRISMA Flow chart for studies selection

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Risk Bias Assessment

Table 1 shows the risk of bias assessment using the Newcastle-Ottawa Scale (NOS). Out of 11 studies, seven studies showed low risk bias, 1 showed high risk bias and the rest of the three studies showed moderate risk bias. In some studies, a portion of their methodological flaw is the way they chose their controls. Furthermore, the inclusion of a cohort study may lead to a high-risk bias assessment of one study **(Table 1).**

The studies included in this systematic review had low-quality risk bias, according to GRADEpro GDT. The primary reasons for the low-risk bias assessment were the inclusion of original studies, which raises the possibility of low-risk bias as it cannot randomize the exposure, and the uneven character of the study."

Table 1: Risk of bias assessment in the studies included in this systematic review.

Study	**Selection**				**Comparability**	**Exposure**		
	1.	**2.**	**3.**	**4.**	**1.**	**1.**	**2.**	**3.**
(Benn and Westerhoff, 2008)	★	★			★★	★	★	★
(Geranio et al., 2009)	★	★			★	★	★	
(Kulthong et al., 2010)	★	★				★	★	★
(Windler et al., 2012)	★	★			★★	★	★	★
(Yan et al., 2012)	★	★	★		★	★	★	★
(Lombi et al., 2014)	★	★			★★		★	★
(Limpiteeprakan et al., 2016)	★	★		★	★★	★	★	★
(Reed et al., 2016)	★	★	★		★	★	★	★
(Wagener et al., 2016)	★	★			★★	★	★	★
(Gorka and Gorham, 2018)	★	★					★	
(Gagnon et al., 2019)	★	★			★★	★	★	★

Rating scale: 7 to 9 stars = low risk of bias; 4 to 6 stars = moderate risk of bias; 0 to 3 stars = high risk of bias

Characteristics of included studies

The objects of the systematic review are distinguishably diverse and concern the release behaviors of silver nanoparticles (Ag-NPs) from nano-textiles under various scenarios. Eleven of the studies analyzed were between the years 2008 to 2019, with most of the studies either

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using comparative or retrospective design to a certain extent with an experimental base. These studies were carried out in the US, Switzerland, Thailand, China, Australia, Germany and Canada. The following findings show that there is the appearance of silver which depends on the type of textile, washing condition type of detergents, and others. For example, some works mentioned that up to 50% of silver was removed with wash water and others aimed at the major forms of released silver and these included ionic particulate forms concerning the water pH and washing technique. Taken together, these works highlight the role of the textile manufacturing processes and functionalization techniques in influencing the release of silver to the environment of commercial nano textual consumer products.

Table 2: Characteristics of Included Studies

Citation	Publication year	Study Design	Country	Key Findings
(Benn and Westerhoff, 2008)	2008	Experimental study	USA	Both colloidal and ionic silver are suggested to leach from the socks by both physical separation and ion selective electrode (ISE) tests. Different sock kinds' varying leaching rates imply that the sock manufacturing procedure may regulate the silver release.
(Geranio et al., 2009)	2009	Experimental study	Switzerland	During the washing machine trials, at least 50% (typically more than 80%) of the total amount of silver freed in the washing fluid was discovered in the >0.45 µm fraction. As a result, a considerable amount of mechanical stress was employed in the washing machine cycle. Generally speaking, the textile industry's share of the overall amount of silver released fluctuated between less than 1% and 45%.
(Kulthong et al., 2010)	2010	Comparative Experimental Design	Thailand	The quantity of silver coating, the quality of the fabric, or the artificial sweat formulations, particularly their pH, were expected to have an impact on how much silver was released from the various materials.
(Windler et al., 2012)	2012	Experimental study	Switzerland	Based on size fractionation, almost equal numbers of particles beneath and above 0.45 µm were discharged. Only two textiles had considerably reduced Ti contents after ten washings. According

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				to electron microscopy, the TiO2 particles that were released into the washing solutions had a spherical shape and formed tiny aggregates of up to 20 particles. The principal particle sizes ranged from 60 to 350 nm.
(Yan et al., 2012)	2012	Experimental study	China	It was proposed as a potential mechanism, and the show that the release performance and current forms of the the nano- silver are different throughout the three simulated conditions. It is shown that the released silver is in the form of ionic forms and sub-micrometer particles in the acid sweating solution. Silver ions make up the majority of the final state of silver in the alkaline sweat solution. Most of the released silver is kept in the presence of nanoparticles in the salt sweat solution, despite partial agglomeration.
(Lombi et al., 2014)	2014	Retrospective study	Australia	Ag-speciation changed significantly after washing using two different detergents. In certain textiles, the two detergents caused a comparable transformation; but, in other textiles, they produced distinct Ag species. This work shows that a variety of distinct Ag species coexist prior to and following washing in functional Ag textiles.
(Limpiteeprakan et al., 2016)	2016	Experimental Design	Thailand	After 20 washes using Milli-Q water, the percentage of Ag that remained in the consumer goods was discovered to be between 46 and 70%. After 20 washing cycles, an independent t test statistical examination of the Ag release rate in Milli-Q washing water comparing consumer items and lab-prepared materials revealed no significant difference ($p > 0.05$).
(Reed et al., 2016)	2016	Comparative Experimental Design	USA	According to toxicity testing, the remaining detergent showed a more negative reaction than the silver that was discharged. Even for textiles that maintained as little as 2 µg/g Ag after washing, the antimicrobial efficacy of the fabrics was shown to be unaffected by the washing process, despite the fact that the clothes did release silver. This was

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				proved by the textiles' >99.9% inhibition of E. coli growth.
(Wageneer et al., 2016)	2016	Comparative Experimental Design	Germany	The findings seem to point to the functionalization type as the primary factor influencing the migration. Furthermore, there is evidence that atomic modifications, such as surface coating, may also affect the Ag-NPs' dissolution behavior in the sweat solutions after measuring various Ag-NP types in their pure form using inductively coupled plasma mass spectroscopy in the single particle mode.
(Gorka and Gorham, 2018)	2018	Experimental Design	USA	Zone of inhibition (ZOI) testing was used to assess the effect on antimicrobial efficacy; following simulated human exposure, there was no discernible difference between the pristine wound dressing and the exposed group. According to the results shown here, AgNM-containing wound dressings undergo a chemical transformation in human fluid simulations, producing a material with antimicrobial qualities similar to those of pristine wound dressings.
(Gagnon et al., 2019)	2019	Comparative Experimental Design	Canada	After the third cycle, there was a 29% drop in the amount of silver in the walking socks. Wearing increased the amount of smaller sized particles (about 50 to 100 nm) in the wash water, with silver constituting the majority of the particles (≥92%; particles >1-2 nm). The Ag-NMs' imaging revealed that silver sheet-like structures, measuring just 67 ± 56 nm in thickness, made up 54% of the particles that were studied. This data collection can be used as a guide for future research and development of artificial wearing techniques.

4. DISCUSSION

The published research on the release of nanoparticles from commercial nano-textiles especially the Ag-NPs presents useful information that contributes to the likely environmental and human health impact of nano-textile technology. Several themes come to light in the 11

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studies contained within this systematic review, including the effects of textile manufacturing processes, the conditions under which nanoparticles are liberated, and the differing characteristics of nanoparticle alteration in different environments.

Another significant discovery of the investigations is that manufacturing processes significantly affect the release of nanoparticles (Mitrano et al., 2014). Benn et al proved that the manufacturing process of socks could control the release of silver, which shows the release rates were different in different socks. In support of this revelation, Reed et al. (2016) stated that when analyzing the antimicrobial properties of the fabrics, it was clear that even if a large amount of nanoparticles were released initially, the properties were not significantly affected (Reed et al., 2016). This raises issues concerning the long-term performance of nano-textiles towards the functional purpose, implying that the desquamative character of silver from the fabrics, which requires periodic regeneration, could be inimical to the effectiveness of nano-textiles as antimicrobial agents but may rather depend on the initial manufacturing and functionalization of fabrics (Mishra and Militky, 2018).

Washing conditions also have a critical influence on the emission of nanoparticles as the previous findings have suggested. Similarly, Geranio et al. (2009), where greater than 50% of silver was observed during machine washing, the mechanical stress, was taken to be important (Geranio et al., 2009). For example, Yan et al. (2012) have shown that when different sweat solutions are used to wash textiles, then different forms of silver are released (Yan et al., 2012). This difference between ionic and particulate silver has a profound impact when identifying the released nanoparticles’ fate. Other researches such as Lombi et al. (2014) also established how various types of detergent affect the release and transformation of nanoparticles, the same way various species of Ag are released (Lombi et al., 2014). These implications suggest that nanoparticle release and change are both product-specific and condition-based and this knowledge should be taken into account when reviewing the environmental safety of nano-textiles (Kaounides et al., 2007, Rather et al., 2020).

One more factor is the change in nanoparticles’ properties after their release into the environment is another factor. Windler et al noted that TiO2 nanoparticles in this study preferred to exist in the aggregate state by being discharged from textiles (Windler et al., 2012). This implies that nanoparticles when released to the environment, may not be in the same particle size as initially designed (Mitrano et al., 2016). However, in light of the observations made by Wagener et al. (2016) one can comment that functionalization methods like surface coating can affect nanoparticle dissolution behaviors (Wagener et al., 2016). Such transformations could change the mobility of nanoparticles in the released environment and their toxicity at that. The accumulation of particles for instance may decrease their activity, while on the other hand, it may also promote their accumulation in living organisms (Singh et al., 2022, Som et al., 2011).

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While there has been the dissemination of nanoparticles there have been some concerns pointed out that suggest that some nano-textiles maintain a considerable quantities of nanoparticle upon washing. According to Limpiteeprakan et al, (2016) the repeatability wash retention ranged between 40 to 70% after 20 wash cycles (Limpiteeprakan et al., 2016). It does not agree with other evaluations such as Gagnon et al. (2019) where large quantities of silver emissions were deposited during initial wash cycles (Gagnon et al., 2019). Some of the findings were that this release behavior could be dependent on the incorporation technique of nanoparticles into the textile matrix; some textiles perhaps are more efficient in encapsulating the nanoparticles within themselves (Khandual et al., 2020). This also implicates the unpredictable functionality of the nanoparticles in real conditions where things are much different than that of the laboratory, for instance, water pH, detergent composition, type of textile, and so on (Yetisen et al., 2016).

The possible dispersion of nanoparticles to the environment attracts significant concerns. The concentration and distribution of released silver nanoparticles may have undesirable effects on ecosystems due to the particles' antimicrobial activity (Kumar et al., 2020). Also, the change of a nanoparticle into another species of nanoparticle as seen by Lombi et al. (2016) affords that the effects of the released nanoparticles on the environment could depend on the form in which they are released (Lombi et al., 2014). Ionic silver, such as is more lethal to water life than the particulate version; therefore, fabrics emitting active ionic silver likely present even more of a threat (Khodaparast et al., 2018).

Furthermore, there are sociological concerns; nano-textiles themselves are beneficial for humans in cases of skin exposure. As Saleem and zaidi (2020) observed, using SEM-EDX, only minor amounts of silver ions are released in artificial sweat, thus suggesting human exposure conditions such as perspiration may release the nanoparticles (Saleem and Zaidi, 2020). This implies that nano-textiles might work as a reservoir of prolonged continuous low-intensity exposure to nanoparticles effects on human health are still unknown. While some studies, for example Gorka and Gorham (2018) showed that wound dressings do not lose their antimicrobial efficiency after imitation of conditions in the human body, the possibility of the chemical changes in the human body remains unanswered (Gorka and Gorham, 2018).

This study indicates that the behavior of nano-textiles and the release of nanoparticles depends on manufacturing processes, application contexts, and environmental conditions. The differences in release rate observed in a given textile under varying conditions and in different kinds of textiles raise the issue of whether a standard safety assessment approach for nano-textiles could be adequate (Rahaman and Khan, 2024). Rather, more accuracy can be achieved by evaluating the resilience of textiles according to the settings within which the textile products will be used. Additionally, the long-term effects of nanoparticles on environmental end impact on health are still inconclusive, therefore this area should attract further study. Subsequent research should concentrate on establishing the protocols for the assessment of

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released nanoparticles and on the methods for reducing the emission of toxic nanoparticles during the manufacturing process and materials regulation (Mondal et al., 2022).

5. CONCLUSION

The release of nanoparticles from consumer products nano textiles especially for silver particles is complex depending on the manufacturing process of the textile, wash conditions, and functionalization methods. As a result, while many nano textiles boosting, continued their antibacterial characteristics even with a great number of nanoparticle releases, it cannot but to mention the environmental and human health risks of nanoparticle release such as the conversion of nanoparticle into toxic ions or particle forms. The inconsistent release behaviors under the different conditions suggest that repeated studies employing standard conditions and regulating testing methods are required for real-world scenario exposures as well as the mechanical health impacts of nanoparticle exposure. The risks related to the impacts of nano-textiles are still tractable; however, implementing better manufacturing and increasing governmental control of the utilization of nano-textiles is crucial.

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