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Impacts of Nanosilver-Based Textile Products Using a Life Cycle Assessment

Hani A. Abu-Qdais [1,*], Muna A. Abu-Dalo [2] and Yazan Y. Hajeer [3]

1 Civil Engineering Department, Jordan University of Science and Technology, P.O.Box 3030, Irbid 22110, Jordan
2 Chemistry Department, Jordan University of Science and Technology, P.O.Box 3030, Irbid 22110, Jordan; maabudalo@just.edu.jo
3 Graduate student, Chemical Engineering Department, Jordan University of Science and Technology, P.O.Box 3030, Irbid 22110, Jordan; yyhajeer18@eng.just.edu.jo
* Correspondence: hqdais@just.edu.jo

Abstract: Due to their properties, silver nanoparticles (AgNPs) are widely used in consumer products. The widespread use of these products leads to the release of such nanoparticles into the environment, during manufacturing, use, and disposal stages. Currently there is a high margin of uncertainty about the impacts of nano products on the environment and human health. Therefore, different approaches including life cycle assessment (LCA) are being used to evaluate the environmental and health impacts of these products. In this paper, a comparison between four different AgNP synthesis methods was conducted. In addition, four textile products that contain AgNPs were subjected to comparison using LCA analysis to assess their environmental and public health impacts using SimaPro modeling platform. Study results indicate that using alternative methods (green) to AgNPs synthesis will not necessarily reduce the environmental impacts of the synthesizing process. To the best of our knowledge, this is the first study that has compared and assessed the environmental burdens associated with different nanosilver-based textile products at different disposal scenarios. The synthesis of 1 kg of AgNPs using modified Tollens' method resulted in 580 kg CO_2 eq, while 531 kg CO_2 eq resulted from the chemical approach. Furthermore, the manufacturing stage had the highest overall impacts as compared to other processes during the life cycle of the product, while the product utilization and disposal stages had the highest impacts on ecotoxicity. Sensitivity analysis revealed that under the two disposal scenarios of incineration and landfilling, the impacts were sensitive to the amount of AgNPs.

Keywords: silver nanoparticles; life cycle assessment; nanosilver textiles; AgNP synthesis; environmental and health impacts

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1. Introduction

For thousands of years, people have known the antimicrobial properties of silver. The Ancient Greeks used silver tanks to preserve potable water. Since the 19th century, silver-enabled compounds have been applied for medical purposes in wound therapy [1]. In the 21st century, silver applications have continued and have been influenced by the development of nanotechnology. Silver has been fabricated as silver nanoparticles (AgNPs), which are fine particles of metallic silver with a size less than 100 nm in at least one dimension. AgNPs exhibit increased activity to weight ratio compared to bulk silver, due to their large surface area. Therefore, the applications and uses of AgNPs have witnessed an increase in different areas, including textiles, medicine, water treatment, and many others [1]. Annually, more than 400 tons of AgNPs are produced globally, where 30% of that quantity finds its way into medical applications [2].

According to the Project on Emerging Nanotechnologies (PEN) in 2015, about 1814 nano-based consumer products have been listed, and silver is the most frequently used nanomaterial (435 products), representing 24% of nano-enabled consumer products [3]. It has been estimated that annually the United States produces between 2.8 and 20 tons of AgNPs [4]. Nevertheless, health and fitness are the largest category containing nanosilver products [4], which includes textiles such as socks, shirts, sport clothes, and more due to their antibacterial properties.

Thousands of tons of silver compounds are estimated to be released to the environment annually, only a fraction of which is nano-silver, and its toxicological effects on the environment and on human health remain unknown [5]. However, these increasing commercial production volumes of nanosilver products and their use generally has led to extensive research into potential environmental and health impacts of their production, use, and disposal. It cannot be ruled out that the increased reactivity of silver nanoparticles due to high surface area may lead to increased toxicological effects on the environment [6,7]. However, the toxic effects are proportional to the rate of release of silver ions (Ag^+) in their life cycle.

As such, there are still many questions that need to be answered regarding the human health and environmental impacts of silver nanoparticles during several stages of their life cycle, including manufacturing, use, and disposal; for example, the stability of these AgNP products across their life cycle, mechanism of release, and how they will behave in the environment.

Life cycle assessment (LCA) is one of the tools that can be used to clarify these questions for products and processes, as well as to assess their potential environmental impacts [8]. It is a cradle to grave study, used to analyze and evaluate the environmental and human impacts of products during all stages of their life cycle [9].

The LCA focuses on the environmental sustainability impacts such as energy, water, and material consumption during the manufacturing and use of the products that contains nanoparticles. LCA enables the splitting of the impacts into categories, such as global warming, acidification, and ecotoxicity. However, the risk assessment focuses on the toxic impacts of the nanoparticles. Therefore, LCA could provide a comprehensive overview of the environmental impacts of the nanoproducts [10], which can compare between products containing nanoparticles with conventional products to evaluate the additional environmental burdens that may be posed by nanoparticles, so as to avoid or minimize them [11]. Therefore, LCA may provide a tool to enhance environmental sustainability as a result of manufacturing and using the nanoproducts, by reducing the energy consumption for instance [12]. In addition, it can be used to compare the effects of nanoproducts with the conventional products. This paper assessing both healt and environmental impacts of AgNP-enabled textiles during their life cycle including production, use, and disposal stages using SimaPro modeling platform and literature data.

1.1. Raw Materials

The major raw materials considered include silver nanoparticles (AgNPs) and textiles, which are commercially produced from cotton and/or polyester. The assessed environmental impacts cover different stages of the life cycle, including the synthesis of AgNPs, the production of textile itself, silver content, and the attachment method in the textile.

1.2. AgNPs Production

Recently, the synthesis of AgNPs has drawn significant attention due to their enhancement of the antimicrobial activity [13]. This includes formation and release of silver ion (Ag^+) and AgNPs themselves during the production. However, there are various techniques to synthesize AgNPs, resulting in different sizes, shapes, and surface properties. The most common ones are physical and chemical techniques. The physical techniques have far fewer applications than the chemical techniques because physical methods have been reported to contain surface imperfections and the morphonology of the particles produced is difficult to control. Thus, chemical reduction synthesis is more extensively used in the manufacturing process [13]. Lately, "green chemistry" has been applied to the synthesis of AgNPs, which aims to reduce the environmental and human health impacts associated with the synthesis methods by using nontoxic reagents, which could be extracted from nature such as through plants or agricultural waste [14]. However, the majority of AgNPs are synthesized using silver nitrate as the source of silver and a reducing agent and a capping agent, which varies according to the synthesis method.

1.3. AgNP-Enabled Textiles

Cotton and polyester are the major materials that are used in AgNP-enabled textiles. In addition, there are different methods used for the combination the AgNPs in the textiles and different silver content, with this leading to the release of different amounts of silver from textiles during their life cycle and thus different environmental effects. A summary of silver content in different types of textiles for different LCA studies was generated from literature and presented in Table 1.

Table 1. Different silver content for different types of nanosilver-enabled textile products (compiled by the authors).

Textile Type	Silver Content (μg Silver/g Textile)	References
Six types of socks	0.9–1358.3	[15]
Nine socks with different compositions	3–21,600	[16]
Antibacterial fabrics	0.99–15.1	[17]
Textiles (different customer products used in the home)	30–270	[18]
Five types of textiles	15–14,500	[19]
Socks available in Polish shops	8.23–20.94	[20]
Cotton filled with AgNPs	4.959–182.1	[20]

1.4. End of Life

In general, textiles are disposed in municipal solid waste stream and may find their way to incinerator or landfill. However, AgNPs released during use stage (laundering) are incorporated with municipal and water house effluents to wastewater treatment plants, contributing to measurable AgNPs concentrations in wastewater. These particles in treatment plants may be removed by treatment processes and usually end up in the sludge as a final sink [4]. If the sludge will be utilized as biosolids for crop production or will be subjected for treatment and disposal by incineration and landfilling, AgNPs will find their way to the environmental systems and may cause a public health risk through the drinking water and or the food chain [21].

Several studies related to AgNP release from commercial products such as clothing fabric and washing machines have been conducted [15,16,22,23]. The results showed a significant amount of AgNP release from these products to the environmental systems. However, few studies have researched the release of nanoparticles under different conditions, with and without detergents; different temperatures; and different types of clothing fabric to identify the effects of these factors on the quantity and form of released silver ions.

In this paper, a cradle-to-grave study using LCA was carried out to assess the footprint from both environmental and health effects perspectives of the enabled AgNP textiles. A comparative LCA analysis of nanosilver-based textile products during different stages of life cycle including AgNPs synthesis process, textile production, usage, and disposal. The LCA analysis covers four AgNPs synthesis methods; four AgNPs textile products; and two disposal scenarios, namely, incineration and landfilling. Different synthesis methods (chemical, physical, and green) were investigated, which represent commercial and laboratory scale, in terms of stoichiometric materials balance, reported energy consumption, and process input and output. To the best of the authors' knowledge, this is the first study that has compared and assessed the environmental and health burdens associated with different nanosilver-based textile products including different disposal scenarios.

2. Methodology

2.1. Scope and System Boundaries

One of the prerequisites to conduct LCA analysis is to identify the system boundaries. Figure 1 presents the system boundaries of the current LCA study. As it can be seen from Figure 1, four synthesizing methods of AgNPs were considered along with their inputs and outputs materials, which are described in the next section. Environmental impacts were analyzed and compared on the basis of synthesizing of 1 kg of AgNPs by each method. In addition, a comparative study was carried out between four different AgNP textiles products, namely, one pair of socks, two types of T-shirts, and medical bandage. The LCA's inventory data were obtained from the literature [2,24–26]. Moreover, the release of AgNPs during the product use stage of the textiles was assumed to be limited to the release of silver during the washing process of textiles, during which most of the nanoparticle release may occur, which is in line with the assumptions made by other researchers [4,20,24]. The potential impacts in the disposal stage of these products were analyzed under both incineration and landfill disposal scenarios.

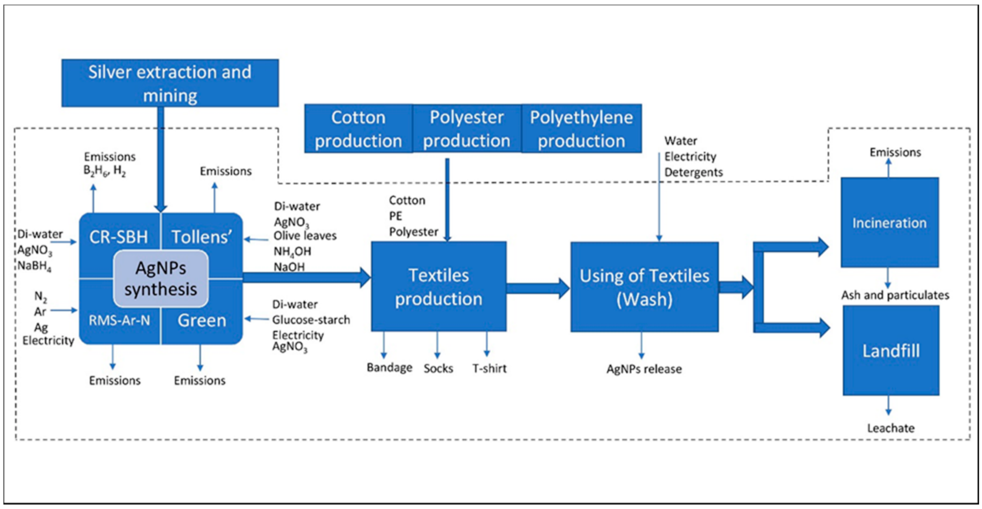

Figure 1. System boundary of various stages of silver nanoparticle (AgNP) life cycle.

2.2. AgNP Synthesis Routes

For the purpose of this study, chemical, physical, and green AgNP synthesis methods were considered. The chemical reduction method used sodium borohydride as a reducing agent [27], while the physical method used reactive magnetron sputtering (RMS) with an argon and nitrogen gas mixture [2]. On the other hand, 2 green methods were selected: glucose-starch method, which uses glucose as a reducing agent [26], and the modified Tollens' method in conjunction with a phytochemical approach [28]. The life cycle inventory data are given in the following section.

2.2.1. Chemical Method

Chemical reduction of silver nitrate with sodium borohydride (CR-SBH) is considered as the most common chemical method for AgNP synthesis, due to its easiness, as it can be carried out using simple equipment [29]. The reduction of silver nitrate $AgNO_3$ solution using ice bath of sodium borohydride $NaBH_4$, the reducing agent, is based on the balanced reaction equation below [27],

$$AgNO3 + NaBH_4 \rightarrow Ag + \frac{1}{2} H_2 + \frac{1}{2} B_2H_6 + NaNO_3 \quad (1)$$

Stoichiometric calculations were performed on the basis of chemical reaction Equation (1), the amounts of reactants and byproducts for producing 1 kilogram of AgNPs as the main product. Hence, 0.35 kg of $NaBH_4$ needs to reduce 1.57 kg of $AgNO_3$, and 0.009 kg of hydrogen gas, 0.128 kg of diborane, and 0.787 kg of sodium nitrate are produced as byproducts. Similarly, the synthesis of 1 kg sodium borohydride needs 2.5 kg of sodium hydride NaH and 2.74 kg of trimethyl borate $C_3H_9BO_3$. The synthesis of 1 kg sodium hydride needs 0.958 Kg of sodium and 0.0416 kg of mono hydrogen.

2.2.2. Green Methods

Modified Tollens' Mehod

There is an environmental demand for alternative methods for AgNPs synthesis that use less toxic reagents and produce less byproducts in order to reduce the environmental effects and emissions. Thus, phytochemicals from plant leaves extracts could be used as reducing agents, instead of toxic borohydride used in the chemical reduction method. Here, we consider a modified Tollens' method used by Abu-Dalo et al. [28], which utilized olive and rosemary leaves extracts to reduce the Tollens' reagent $[Ag(NH_3)_2]^+$ to AgNPs. In terms of the stoichiometric calculations, 1.57 kg of $AgNO_3$, 0.315 kg of NH_3, and 0.369 kg of NaOH need to produce 1 kg of AgNPs. To complete the life cycle inventory, we assumed the amount of leaf extract to be 4 kg of olive leaves, which are needed to reduce 1.31 kg of Tollens' reagent and to produce 1 kg of AgNPs. All the previous inputs are based on the following chemical reactions of Equations (2)–(4) [28,30,31].

$$2\,AgNO_3 + 2\,NaOH \rightarrow Ag_2O + 2\,NaNO_3 + H_2O \tag{2}$$

$$Ag_2O + 4\,NH_3 + 2\,NaNO_3 + H2O \rightarrow 2[Ag(NH_3)_2]NO_3 + 2\,NaOH \tag{3}$$

$$[Ag(NH_3)_2]^+ + RCHO + H_2O \rightarrow 2\,Ag + 4\,NH_3 + RCOOH + 2\,H^+ \tag{4}$$

Glucose-Starch (GS) Method

This is one of the green methods used lately to synthesize AgNPs, which use glucose to reduce the silver nitrate and corn starch as the stabilizing agent. The process is performed using a microwave for heating, and thus it is called a microwave-synthesized method of AgNPs. Materials and energy inputs for this process are based on a study performed by Bafana et al. [26], using 2.5 kg of Glucose and 1.31 kg corn starch to reduce 1.57 kg of $AgNO_3$. The electricity used for microwave usage was estimated to be 1250 MJ.

2.2.3. Physical Method Reactive Magnetron Sputtering (RMS) with an Argon and Nitrogen Gas Mixture.

Reactive magnetron sputtering (RMS) of silver with an Argon and Nitrogen gas mixture method, is considered one of the physical methods used to synthesize AgNPs, also known as physical vapor deposition. It uses argon (inert gas) and nitrogen gas mixture to bombard the sputtering metal (silver) and cause eviction of Ag^+ (silver oxides or nitrides), which is deposited onto the substrate [2]. Material and energy inputs for this process were obtained as mentioned by Pourzahedi et al. [2], wherein they were estimated on the basis of experimental results cited by Pierson et al. [32]. To produce 1 kg of AgNPs, 10.4 g of N_2 gas and 124 g of Ar gas are needed. In addition, 27.8 kWh of electricity is required.

2.3. AgNP-Enabled Textiles

The textiles considered in this study are (1) sock made from 60.8 g of knit cotton and incorporated with 10.2 mg of AgNPs, based on a study performed by Meyer et al. [24]; (2) two types of T-shirts, one made from polyester and the another from cotton, with both consisting of 130 g of textile material incorporated with 31 mg of AgNPs [33]; (3) Acticoat7 bandage made from 0.69 g high density polyethylene and 0.7 g of polyester and incorporated with 130 mg of AgNPs [2]. For comparative studies purposes, each of the 4 mentioned textiles were modeled as produced with and without nanosilver. Table 2 shows details of the 4 textile products used in this study.

Table 2. Characteristics of the nano products that were analyzed in this study.

Textile Product	Textile Material	Silver Content (mg)	Textile Mass (g)	Silver Content (wt/wt) %
Acticoat7 bandage	Polyester and HDPE	130	1.3	10
Cotton T-shirt	Cotton	31	130	0.024
Polyester T-shirt	Polyester	31	130	0.024
Sock	Cotton	10.2	60.8	0.017

2.4. Life Cycle Assessment Model

The life cycle assessments in this work were performed using SimaPro 9.0 software, which was developed by PRé Sustainability [34] as a suitable LCA modeling platform. It is provided with ecoinvent v.3 database [35] with several unit processes, methods of analysis, and tools. Environmental and health impacts in this study were modeled by the widely used midpoint model tool for the reduction and assessment of chemical and other environmental impacts, TRACI 2.1, which has been expanded and developed for sustainability metrics and expresses impacts in terms of discrete environmental effects [36]. This method covers the following impacts categories followed by their units for each: global warming (kg CO_2 eq), ozone depletion (kg CFC-11 eq), smog formation (kg O_3 eq), respiratory effects (kg PM2.5 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), toxic carcinogenic and noncarcinogenic substances (CTUh), fossil fuel depletion (MJ surplus), and ecotoxicity (CTUe) [8].

SimaPro 9.0 that is integrated with ecoinvent v.3 database and TRACI 2.1 method include most updated unit process, system process, and different industries. Furthermore, the developed model in this study assessed the environmental and health impacts by considering the used materials, implemented processes, amount of energy and water utilized, and inputs and outputs. For such an emerging technology as nanotechnology, there is a potential for uncertainty in assessing the impacts during all stages of AgNPs' life cycle. According to Pourzahedi and Eckelman [2], there is a need to reduce such uncertainty, while Hicks et al. [4] indicated that the highest uncertainty level is associated with the use stage of the products.

3. Results and Discussion

3.1. Impacts from AgNP Synthesis Processes

In this study, a comparative environmental impact analysis between the four-synthesis methods of AgNPs was first performed on the basis of the material and energy required in the process of synthesizing 1 kg of AgNPs. The relative comparative results are shown in Figure 2. The results indicate clearly that the modified Tollens' method has the highest potential impacts across all categories except for acidification and non-carcinogenic impacts. These relatively high impacts are due to the use of large quantities of de-ionized water in this process. The chemical method ranked second for the same reason. For example, the synthesis of 1 kg of AgNPs using modified Tollens' method resulted in 580 kg CO_2 eq, while 531 kg CO_2 eq resulted from the chemical approach.

The other two methods (glucose starch and physical) have less impacts due to the use of smaller amount of water in the case of the GS method or in the absence of water in the physical method. The results also indicate that the major contribution processes for all synthesizing methods are the mining and refining processes of silver, which is considered part of the silver extracting stage that includes three processes: (i) use of crude oil, coal, and natural gas as energy sources that mainly affect fossil fuel depletion; (ii) release of zinc, chromium, and copper metals into the air and soil, which highly affects the ecotoxicity, and release of lead and mercury, which has an effect on carcinogenic and noncarcinogenic impacts; (iii) emissions of Sulfur and Nitrogen dioxides (SO_x and NO_x) , which could increase acidification and eutrophication impacts. Similar results were obtained previously by Pourzahedi and Eckelman [2,25].

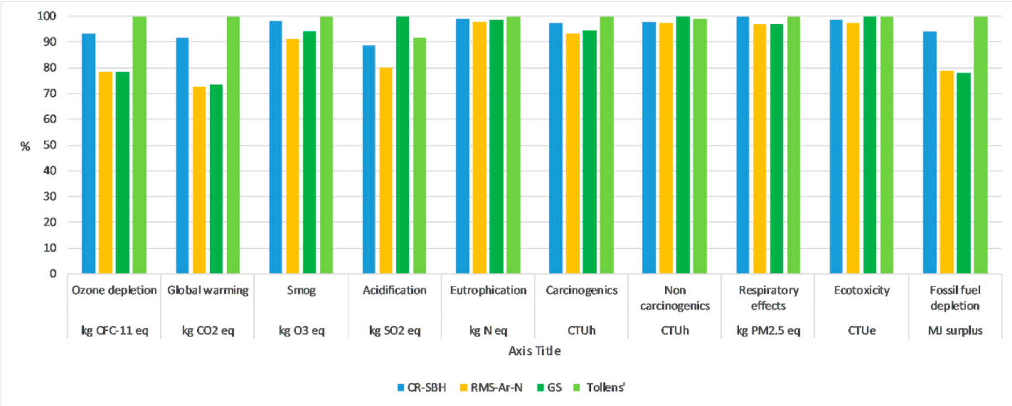

Figure 2. Environmental and health impacts of producing one kilogram of AgNPs using four synthesizing methods.

To enhance the understanding of process contribution for each impact category, we show in Figure 3a–d the process contributions of the four synthesizing methods. In addition to the aforementioned clarifications, we noted that the GS method has the highest effects on acidification and non-carcinogenic impacts, due to the use of electricity in the microwave system [26].

These results indicate that the use of green or modified methods that are considered as alternative methods to the chemical and physical methods in synthesizing the silver nanoparticles will not necessarily reduce the environmental effects of the product during its life cycle, as these methods use higher amounts of water and electricity, which is reflected on the water and carbon footprints of such synthesis methods. As such, further research is required to find new alternative synthesizing methods with lower impacts.

Moreover, regarding the reducing agents used in each method, sodium borohydride, olive leaves, glucose, and argon gas have relatively low impacts as compared to the impacts of using silver source ($AgNO_3$ or silver) and de-ionized water. To minimize the environmental impacts of silver, Pati et al. [37] proposed the use of recovered silver from spent solutions instead of extracting it from nature. However, it was found that sodium borohydride has the highest impacts under all categories as compared with the other reducing agents, but it showed insignificant impacts compared to silver nitrate contribution. In addition, using of olive, starch, and glucose as benign agents in two green methods resulted in low environmental impacts, as expected [25,26,28].

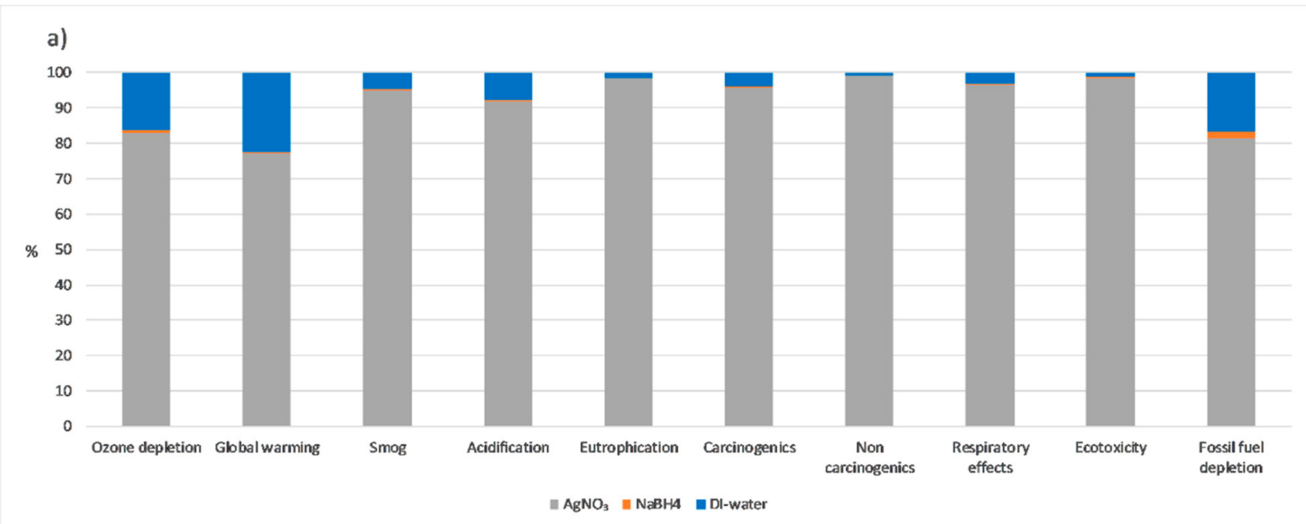

Figure 3. *Cont.*

Figure 3. Detailed contribution of AgNP synthesizing process. (**a**) Chemical reduction of silver nitrate with sodium borohydride (CR-SBH) method, (**b**) modified Tollens' method, (**c**) glucose-starch (GS) method, (**d**) reactive magnetron sputtering (RMS) with an argon and nitrogen gas mixture.

3.2. Impacts from Textiles Production

The environmental impacts of textile manufacturing were carried out using four types of textile products, namely, medical Acticoat7 bandage, cotton socks, polyester T-shirt, and cotton T-shirt, with different textile mass and nanosilver content (as shown in Table 2), and compared with similar conventional textile products that do not contain nanosilver.

In conducting the comparison of various AgNP synthesis processes, we used the functional elements of 1 kg. However, due to the very small values of the impacts obtained, when the full LCA was conducted for the entire life cycle of the product including synthesis, the functional element used was 1000 units. The synthesis process used in the LCA analysis was the CR-SBH method. Figure 4 shows an example of the environmental and public health impacts of various products in terms of material and energy inputs and outputs of the manufacturing process, while Table 3 shows various environmental and health impact categories associated with different textile products. It can be clearly seen that using cotton in producing textiles has more impacts on the environment than the use of industrial polyester (Figure 4, Table 3). When comparing polyester T-shirt to cotton T-shirt (same textile mass and silver content), the cotton T-shirt has greater impacts under all impact categories. In addition, it can be noted that there is a slight difference between cotton socks and cotton T-shirt, although they have different masses. Using cotton in producing the textiles affects the ecosystem as a result of using fertilizers and pesticides to grow the cotton, which leads to the release of the nitrate and phosphate into water bodies that causes to the eutrophication process and increases the ecotoxicity [24]. As can be seen in Table 3, the impact of cotton T-shirt-Ag was more than eight times greater than polyester T-shirt-Ag in both eutrophication (4.2 kg N eq for cotton T-shirt-Ag and 0.52 for polyester T-shirt-Ag) and ecotoxicity (5982 CTUe for cotton T-shirt-Ag and 511 CTUe for polyester T-shirt-Ag). However, relatively high fossil fuel depletion impact in polyester and cotton T-shirts was observed as a result of using fuel through industrial processing. The manufacturing of polyester T-shirt-Ag and cotton T-shirt-Ag resulted in fuel surplus amounts of 2410 and 2874 MJ, respectively.

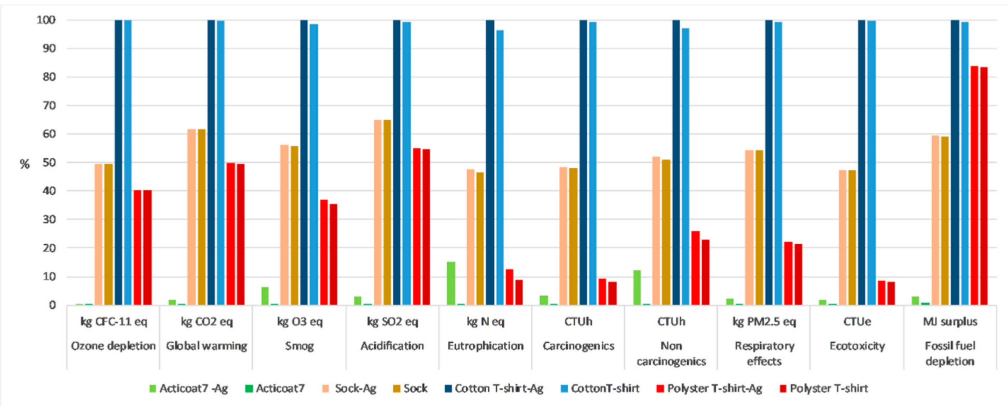

Figure 4. TRACI impacts of manufacturing different textiles products.

Table 3. A comparison between four types of textiles with and without nano silver in terms of manufacturing impacts of 1000 units.

Impact Category	Aticoat7 Ag	Acticoat7	Socks Ag	Socks	Cotton T-Shirt Ag	Cotton T-Shirt	Polyester T-Shirt Ag	Polyester T-Shirt
Ozone depletionkg CFC-11 eq	2.15×10^{-5}	1.14×10^{-5}	0.00292	0.00292	0.00591	0.00591	0.00239	0.00238
% increase	46.84		0.03		0.04		0.10	
Global warmingkg CFC-11 eq	77.569	8.419	2374.047	2368.622	3848.860	3832.370	1922.071	1905.582
% increase	89.15		0.23		0.43		0.86	
Smogkg O3 eq	10.742	0.264	95.849	95.027	170.176	167.678	62.721	60.222
% increase	97.55		0.86		1.47		3.98	
Acidificationkg SO2 eq	0.635	0.030	13.589	13.542	20.848	20.704	11.512	11.368
% increase	95.27		0.35		0.69		1.25	
Eutrophicationkg N eq	0.635	0.005	2.000	1.951	4.201	4.050	0.529	0.379
% increase	99.26		2.47		3.58		28.43	
CarcinogenicCTUh	1.15×10^{-6}	1.87×10^{-8}	1.57×10^{-5}	1.56×10^{-5}	3.26×10^{-5}	3.23×10^{-5}	2.97×10^{-6}	2.70×10^{-6}
% increase	98.37		0.56		0.82		9.05	
Non carcinogenicCTUh	4.08×10^{-5}	3.54×10^{-7}	1.73×10^{-4}	1.70×10^{-4}	3.34×10^{-4}	3.24×10^{-4}	8.59×10^{-5}	7.62×10^{-5}
% increase	99.13		1.83		2.89		11.24	
Respiratory effectskg PM2.5 eq	0.092	0.002	2.095	2.088	3.855	3.834	0.851	0.829
% increase	97.83		0.34		0.56		2.53	
EcotoxicityCTUe	113.941	3.182	2828.561	2819.870	5982.041	5955.629	511.896	485.484
% increase	97.21		0.31		0.44		5.16	
Fossil fuel depletionMJ surplus	87.764	20.309	1706.684	1701.392	2874.005	2857.919	2410.509	2394.423
% increase	76.86		0.31		0.56		0.67	

On the other hand, on the basis of nanosilver content in the textile, we found that the high silver content in Acticoat7 bandage (10 wt%) had a major increase in all categories of environmental and health impacts, ranging from 46% for ozone depletion up to 99% for non-carcinogenic impact category, as shown in Table 3. However, for lower silver content textiles such as the case with T-shirt and socks, the increase in the impact categories was relatively lower due to the low nanosilver content. Considering the large amounts of textile products that are manufactured with AgNPs, such increases should not be neglected due to the potential high cumulative environmental and health impacts.

3.3. Disposal Stage

After the end of the product's useful life, it has to be gotten rid of as an unusable and unwanted item. Therefore, it has to be disposed where such a stage should be assessed in the LCA analysis. In this study, two disposal scenarios were considered for the textile products that contain AgNPs, namely, incineration followed by landfilling and direct landfilling. According to the literature, during the usage stage of the textile products with AgNPs, it is assumed that 50% of the silver nano particles are leached out from the product [4,15,20,33]. As such, the product in the disposal stage contains only half of the silver nanoparticles initially embedded in it during the manufacturing process. For the incineration scenario, researchers estimated that 1% of the nanosilver in the textile is released as fly ash into the atmosphere, while the remaining incinerated AgNPs are caught by an incinerator filtration system and consequently remain in the bottom ash [2,38], which eventually finds its way to landfill. The nanosilver that is released into the air from the incinerator is assumed to be deposited in a large fraction into the soil (93%), while the remaining fraction finds its way to the surface water [2].

The significant difference between the two disposal methods was found for the non-carcinogenic impact category because the potential release of nanosilver into the atmosphere in the incineration scenario was higher than in landfill scenario. The significance of this category was due to the fact that silver is considered a non-carcinogenic metal [39].

The environmental and health impact categories at each life stage in terms of two disposal options of incineration and landfilling for 1000 units of Acticoat7-Ag are presented in Table 4. It can be observed that for most of the categories, the total environmental and health impacts of the landfill option was slightly better than incineration. The only significant difference in the total impact was the one that was related to the no carcinogenic impact category, where the incineration option was higher than the landfill by almost 17%. As for the impact categories of each life stage, it can be seen that for all impact categories, the synthesis stage had the highest values of impacts as compared to other life cycle stages of manufacturing, use, and disposal. For example, the synthesis stage had global warming potential of 73.2 kg of CO_2 equivalent, while the manufacturing and use stages had 0.13 and 0 kg of CO_2 equivalent, respectively.

Table 4. Environmental and health impacts during all life stages of the Acticoat7-Ag bandages in terms of two disposal scenarios.

Impact Category	Unit	AgNPs Synthesis *	Acticoat7 Fabric	Use Stage	Disposal Stage		Total Impacts	
					Incineration	Landfill	Incineration	Landfill
Ozone depletion	kg CFC-11 eq	2.12×10^{-5}	3.69×10^{-7}	0.00	2.08×10^{-7}	-9.04×10^{-9}	2.15×10^{-5}	2.15×10^{-5}
Global warming	kg CO_2 eq	73.20	4.17	0.00	3.91×10^{-1}	−1.06	77.75	76.3
Smog	kg O_3 eq	10.61	0.13	0.00	-2.20×10^{-3}	−0.01	10.83	10.73
Acidification	kg SO_2 eq	0.62	0.02	0.00	3.16×10^{-3}	-4.70×10^{-4}	0.638	0.634
Eutrophication	kg N eq	0.63	3.47×10^{-3}	0.00	-3.73×10^{-5}	-4.36×10^{-3}	0.636	0.634
Carcinogenic	CTUh	1.14×10^{-6}	9.09×10^{-9}	0.00	5.90×10^{-11}	-1.83×10^{-10}	1.15×10^{-6}	1.14×10^{-6}
Non-carcinogenic	CTUh	5.21×10^{-5}	1.99×10^{-7}	1.55×10^{-5}	1.96×10^{-5}	8.09×10^{-6}	9.14×10^{-5}	7.59×10^{-5}
Respiratory effects	kg PM2.5 eq	0.09	1.53×10^{-3}	0.00	2.69×10^{-4}	-1.03×10^{-4}	0.0922	0.0920
Ecotoxicity	CTUe	292.36	2.79	12,490.83	6.49×10^{3}	6502.94	19,280.5	19,288.9
Fossil fuel depletion	MJ surplus	75.14	12.58	0.00	6.07×10^{-1}	−0.15	87.9	87.6

* AgNPs synthesized using CR-SBH method.

In terms of health impacts, Table 3 shows that the respiratory effect of AgNPs bound to Acticoat7 during manufacturing and use stages were increased by 97.83% as compared to Acticoat7 without nanosilver (i.e., from 0.002 to 0.092 kg PM2.5 eq). This increase may be attributed to the emission of nanosilver into the atmosphere during the synthesis process, which is evidenced from Table 4, where almost 98% of the nanosilver was emitted during the synthesis stage (0.09 kg PM2.5 eq out of 0.092 kg PM2.5 eq).

Non-carcinogenic and ecotoxicity impact sensitivity to the amount of the released AgNPs into water during the washing process was assessed for Acticoat7-Ag bandages under the two disposal scenarios. Table 5 shows the values of the impacts compared to the baseline release value of 50%, which was assumed in running the LCA analysis. It can be observed that decreasing the release from 50% to 25% can lead to a decrease of the noncarcinogenic impacts by 12.6% and 6.74% for the incineration and landfilling options, respectively, while similar value of decrease (32.7%) was obtained for the ecotoxicity impact under both disposal scenarios. On the other hand, increasing the AgNPs release by 25% (from 50% to 75%) will increase the noncarcinogenic impact by 12.7% and 7.87% under incineration and landfilling, respectively. Again, similar value of increase (24.6%) was achieved in the ecotoxicity impact value under both disposal scenarios.

Table 5. Sensitivity of non-carcinogenic and ecotoxicity impacts of Acticoat7-Ag life cycle assessment (LCA) at different nanosilver release percentages during the washing process.

Silver Percentage Release into Water	Non-Carcinogenic (CTUh)		Ecotoxicity (CTUh)	
	LCA Acticoat7-Ag (Incineration)	LCA Acticoat7-Ag (Landfill)	LCA Acticoat7-Ag (Incineration)	LCA Acticoat7-Ag (Landfill)
25%	$7.99 \times 10^{-5}(-12.6\%)$	$6.44 \times 10^{-5}(-6.74\%)$	12,975.5(−32.7%)	12,983.9(−32.7%)
50%	9.14×10^{-5}	7.59×10^{-5}	19,280.5	19,288.9
75%	$1.03 \times 10^{-4}(12.7\%)$	$8.74 \times 10^{-5}(7.87\%)$	25,585.5(24.6%)	25,593.9(24.6%)

Values in brackets indicate the percent change in the impact value as a result of changing the release of AgNPs during washing process of the textile.

4. Conclusions

Nanosilver-containing textiles may have potential environmental and health impacts during production, use, and disposal even at small amounts of nanosilver. In this work, life cycle assessment analysis revealed that impacts associated with AgNP production were dominant for almost every category of environmental impacts. While modified Tollens' and chemical reduction methods were shown to have the highest impacts due their effects on water footprint, global warming, and fossil fuel depletion, insignificant effects were found for green reducing agents compared to the impacts of silver nitrate. Cotton textiles were found to have greater environmental impacts in eutrophication and ecotoxicity than industrial polyester as a result of using fertilizers and pesticides in growing cotton. Moreover, landfill disposal route was found to have an important non-carcinogenic impact. Finally, nanosilver textile product utilization and disposal showed high impacts in ecotoxicity due the potential release of AgNPs, taking in consideration the fact that these impacts can become significant when scaled up to a global level. Further research efforts are recommended to assess the uncertainty involved in calculating the impacts of such an emerging technology during different life stages of nanoparticles, including manufacturing, use, and disposal.

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