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POLICY ANALYSIS

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120 Years of Nanosilver History: Implications for Policy Makers

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Supporting Information

ABSTRACT: Nanosilver is one nanomaterial that is currently under a lot of scrutiny. Much of the discussion is based on the assumption that nanosilver is something new that has not been seen until recently and that the advances in nanotechnology opened completely new application areas for silver. However, we show in this analysis that nanosilver in the form of colloidal silver has been used for more than 100 years and has been registered as a biocidal material in the United States since 1954. Fifty-three percent of the EPA-registered biocidal silver products likely contain nanosilver. Most of these nanosilver applications are silver-impregnated water filters, algicides, and antimicrobial additives that do not claim to contain nanoparticles. Many human health standards for silver are based on an analysis of argyria occurrence (discoloration of the skin, a cosmetic condition) from the 1930s and include studies that considered nanosilver materials. The environmental standards on the other hand are based on ionic silver and may need to be re-evaluated based on recent findings that most silver in the environment, regardless of the original silver form, is present in the form of small clusters or nanoparticles. The implications of this analysis for policy of nanosilver is that it would be a mistake for regulators to ignore the accumulated knowledge of our scientific and regulatory heritage in a bid to declare nanosilver materials as new chemicals, with unknown properties and automatically harmful simply on the basis of a change in nomenclature to the term "nano".

INTRODUCTION

The potential adverse effects of nanoparticles on humans and the environment currently receive a lot of attention both in academia and with regulators.[1,2] A lot of the discussion is centered on the asserted assumption that nanoparticles are something fundamentally "new" and thus cannot be compared to conventional chemicals or bulk materials. Nanosilver is one of the nanomaterials that is under the most scrutiny today[3−5] and its release and effects are studied widely.[6−9] Although changes in nomenclature over the decades have created confusion among scientists and policy makers, it is undeniable that products containing nanoscale silver particles have been commercially available for over 100 years and were used in applications as diverse as pigments, photographics, wound treatment, conductive/antistatic composites, catalysts, and as a biocide. With this long and diverse history of use it is clear that an extraordinary amount of research into the chemistry of nanoscale silver has been conducted over the past 120 years— it should be noted that most research, until very recently, did not use "nano" nomenclature.

In this analysis we critically examine with respect to nanosilver three important assertions often made when discussing risk assessment of silver nanoparticles:

(1) Nanosilver is new and exhibits unique physical and chemical properties compared to "conventional" silver (e.g., macroscale "bulk" silver).
(2) Nanosilver has been used for only a few years and the environment and humans have never been exposed to nanosilver before.
(3) Existing risk assessments of silver have been based on a data set derived from conventional silver materials, so they do not apply to nanosilver.

ANTIMICROBIAL BIOCIDES

Antimicrobial biocides are commonly used to prevent the growth of bacteria on surfaces and within materials and are typically added in small quantities to many applications to make it more difficult for bacteria to grow on the treated object. Biocidal functionality can be achieved by employing either organic or inorganic active agents. Compounds such as quaternary ammonium and chlorinated phenols are examples of two widely used organic chemical biocidal agents. Inorganic active agents are generally based on metals such as silver and copper. Silver has found a growing presence in many applications due to a desire to shift away from organic chemical agents toward additives, which can be used in much lower concentrations in a wider variety of products including applications such as plastics where high-temperature processing is not feasible for organic compounds. Examples of applications are bacteriostatic water filters for household use[10] or swimming pool algicides.[11] To meet the diversity of application types, many different forms of silver compounds have been developed to service this market.

Whereas biocidal action derives from interaction of silver ions with bacteria, silver additives are differentiated primarily by the way the silver ions are stored in the product. Common silver products range from additives that store and release discrete silver ions held within a ceramic (e.g., zeolite) or glass matrix, through to products that store silver ions as silver salts (e.g., silver chloride) or elemental silver (e.g., nanoscale silver metal).

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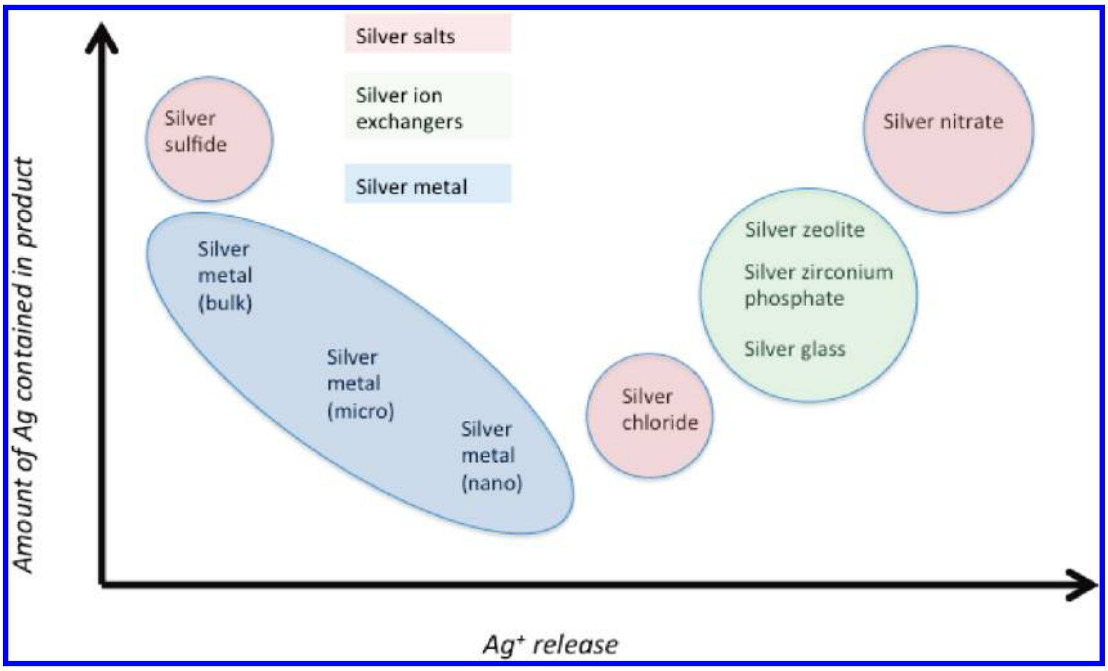

Figure 1. Silver release and amount of silver required in products for different biocidal silver formulations.

Upon contact with moisture, silver ions are released from the additive and the object treated with the additive. The biocidal potency of a silver additive is therefore directly related to the potential for releasing silver ions.[12,13] However, in the case of free nanosilver particles the interactions can potentially be more complex, and catalytic reactions on the particle surface that can change as a function of size and shape of the nanoparticles can complicate the system.[14] It should be noted, however, that most commercial applications of nanosilver involve embedding the particles within a matrix such as a plastic or a coating.

There are two clear "bookends" for illustrating the extremes of the potential for silver ion release from silver substances: namely silver sulfide (highly insoluble, hence a low potential for silver ion release) and silver nitrate (completely soluble, maximum potential for silver ion release). The release potential of different silver materials can be distributed between the silver sulfide and silver nitrate extremes (Figure 1). Materials that store discrete silver ions in a matrix show a high potential for releasing silver ions, only marginally less than silver nitrate. Silver salts such as silver chloride show a lower release potential than the ion-based materials and so are positioned further from silver nitrate. At the other extreme, bulk silver metal (e.g., silver ingot) releases silver ions to a small extent and so has a potential closer to the silver sulfide extreme. As the size of silver metal is decreased from bulk through to micrometer-sized particles through to nanosized particles, the potential for releasing silver ions increases because of increasing surface availability per mass of silver and because both the solubility and dissolution kinetics of silver may vary as a function of size as silver metal size decreases. Therefore the potential for releasing silver ions increases and so the behavior moves away from the silver sulfide bookend toward silver nitrate. It is important to note that while the tendency for higher silver ion release improves with smaller silver particle size, the silver salts and silver-ion materials still show higher potential and antimicrobial activity than the nanosized silver metal materials.[12]

HISTORY OF NANOSILVER PRODUCTION AND USE

One of the standard definitions of nanotechnology encompasses "research and technology development at the atomic, molecular, or macromolecular levels using a length scale of approximately 1−100 nm in any dimension; the creation and use of structures, devices, and systems that have novel properties and functions because of their small size, and the ability to control or manipulate matter on an atomic scale."[15] The unintentional formation of nanoparticles thus would not fall under this definition of an engineered nanoparticle. It is estimated that today about 320 tons/year of nanosilver are produced and used worldwide [16] (data on its historical production are not available). Now what about the first report of nanosilver? Over 120 years ago, in 1889, M. C. Lea reported the synthesis of a citrate-stabilized silver colloid.[17] The average diameter for the particles obtained by this method is between 7 and 9 nm.[18] Their size in the nanoscale and the stabilization by citrate are identical to recent reports about nanosilver formation using silver nitrate and citrate, e.g., refs 19 and 20. Also the stabilization of nanosilver using proteins has been described as early as 1902.[21] Under the name "Collargol" such a kind of nanosilver has been manufactured commercially since 1897 and has been used for medical applications.[22] Collargol has a mean particle size of 10 nm[23] and as early as 1907 its diameter was determined to be in the nanorange.[24] Other nanosilver preparations were also invented in the next decades, for example the gelatin stabilized silver nanoparticles patented by Moudry in 1953 with 2−20 nm diameter[25] and silver nanoparticle impregnated carbon with a diameter of silver particles below 25 nm.[26] It is important to note that the inventors of nanosilver formulations understood decades ago that the viability of the technology required nanoscale silver, e.g., by the following statement from a patent: "for proper efficiency, the silver must be dispersed as particles of colloidal size less than 250 Å [less than 25 nm] in crystallite size".[26] Whereas it is true for many other engineered nanomaterials that they are novel, e.g., for fullerenes and carbon nanotubes, this is

Table 1. Evaluation of National Pesticide Information Retrieval System (NPIRS; http://ppis.ceris.purdue.edu/npublic.htm) Database for EPA-Registered Silver Products

category	conclusion	selection basis	number of registrations
confirmed nano	nano	evaluation based on public citations stating nano nature of product or direct measurements on product material (e.g., Figures 3 and 4)	7 (7%)
likely nano	nano	evaluation based on patent literature and/or manufacturing techniques	42 (46%)
ionic	not nano	products contain materials that store and release individual silver ions	31 (34%)
not likely nano	not nano	products contain macro scale materials, e.g., silver-coated fibers	8 (9%)
unknown	not nano	insufficient information available	4 (4%)

clearly not the case for nanosilver. This long history of rational fabrication and use of colloidal nanosilver has resulted in a lot of research and knowledge about these nanoparticles over the last 100 years, even if this research is not reported under "nano" terminology.

The nanosilver formulations mentioned in the preceding section have not only been used by scientists and described in the patent literature, but have consistently found their way into the market. In the early part of the 20th century, the commercial sale of medicinal nanoscale silver colloids, known under different trade names such as Collargol, Argyrol, and Protargol, began and over a 50-year period their use became widespread. These nanosilver products were sold as over-the-counter medications and also used by medical doctors to treat various diseases such as syphilis and other bacterial infections.[27]

REGISTRATION OF NANOSILVER PRODUCTS IN THE UNITED STATES

Apart from these medical applications, many biocidal nanosilver products were developed and registered in the United States. Information on EPA-registered silver products for the last 60 years is contained in the NPIRS database (National Pesticide Information Retrieval System, http://ppis.ceris.purdue.edu/npublic.htm). We searched and evaluated this database for all registered biocides referring to silver as the active substance, and registered labels relating to each product were reviewed for the form of the silver and the company name. Additional searches in public patent literature and general Internet searches specific to the company and product were also used to evaluate the nature of each registered product. Based on these reviews the list of registered silver products was divided into five categories, from surely containing "nano" to not likely containing "nano" (Table 1).

Of the biocidal silver products, 53% likely or surely contain nanosilver but only 7% are advertised as containing nanoparticles. For the majority of the registered products only a combined evaluation of patents and knowledge on manufacturing techniques and materials science can inform about the nature of the silver present in the product. Figure 2 shows the frequency of EPA-registered silver products over the years. The first biocidal silver product registered in the U.S. under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1954 was Algaedyn, a nanosilver product based on the patent by Moudry[25] that is still used today as an algicide in residential swimming pools. After the establishment of EPA in 1970 all silver registrations in the next 23 years until 1993 were for nanosilver (colloidal silver) or for silver nanocomposites. The first non-nanosilver product was registered in 1994. It is also apparent that the number of "non-nano" silver products has risen substantially in the last 10 years, necessitating also new scientific studies on potential ecotoxicological effects of these "conventional" products.

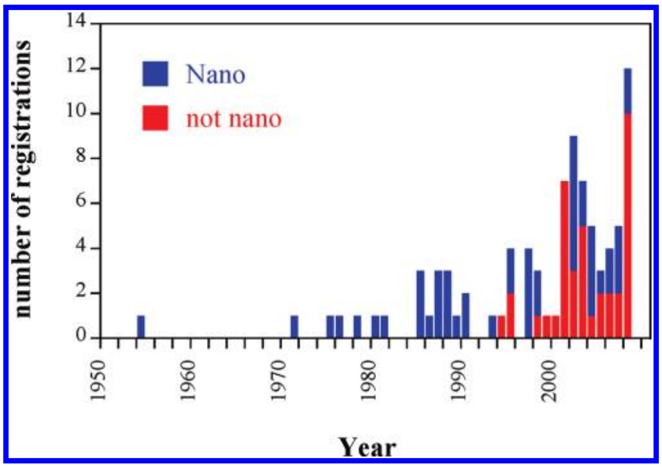

Figure 2. Registration of biocidal silver and nanosilver products in the U.S. with the categorization according to Table 1.

There are at least three categories of EPA-registered products that employ elemental silver particles with particle sizes less than 100 nm: (a) silver biocidal additives; (b) silver-impregnated water filters; (c) silver algicides and disinfectants. Several examples of each category are identified below.

Silver Biocidal Additives. EPA has registered numerous biocidal additives based on elemental silver particles. Table 2 contains some examples of currently registered biocidal additive products that contain metallic (elemental) silver with very small particle size (<100 nm), including Additive SSB (EPA reg. 83587-3, company NanoHorizons), MicroSilver BG-R (EPA reg. 84146-1, company Bio-Gate), and HyGate 4000 (EPA reg. 70404-10, company BASF, formerly Ciba Corp.). These silver biocides are typically used in plastic and textile applications where the silver is effectively contained within polymer substrates.

Silver-Impregnated Water Filters. EPA has registered multiple silver-impregnated water filters since the 1970s. Bacteriostatic water filters are generally based on activated carbon or ceramics that are impregnated with metallic (elemental) silver exhibiting a very small particle size (<100 nm). It should be noted that impregnating carbon and ceramic materials with metals is widely recognized as a standard technique for the synthesis of nanoscale metal particles. In particular, wet impregnation methods have been employed in production of nanostructured industrial catalysts for decades. Numerous peer-reviewed scientific literature publications clearly establish that impregnation methods lead to nanoscale metal particles (e.g., nanosilver) supported on the impregnated substrate (e.g., carbon).[28,29]

Silver-impregnated water filters currently registered under FIFRA employ impregnation-based manufacturing methods to

Table 2. Details about Some Selected EPA-Registered Nanosilver Products

product type	product name	company	EPA registration number	date registered	reference
water filter	989 Bacteriostatic Water Filter Media	Barnebey & Sutcliffe Corp (Now owned by Calgon)	58295-1	1-Dec-1988	[a]
water filter	NATURE2 G45-VC40	Zodiac Pool Care, Inc.	67712-1	21-Nov-2002	[b], Figure 3
algicide	Algaedyn	Pool Products Packaging Corp	68161-1	31-Dec-1954	Figure 4
algicide	Nu-Clo Silvercide	Alden Leeds Inc.	7124-101	15-Jun-1993	[d]
algicide	ASAP-AGX	American Biotech Laboratories	73499-1	27-Feb-2002	[c]
additive	Additive SSB	Nanohorizons Inc.	83587-3	28-Sep-2007	[d]
additive	MicroSilver BG-R	Bio-Gate AG	84146-1	18-Mar-2008	[e]
additive	HyGate 4000	BASF Corp (Formerly Ciba)	70404-10	5-Sep-2008	[e]

[a] US Patent 3,374,608, "Silver Impregnated Carbon" (1968), Pittsburgh Activated Carbon Company, now owned by Calgon ("*activated carbon impregnated with a metallic silver having a crystallite size of* ***not over 250 A*** *[25 nm].*"..."*[T]he silver must be dispersed as particles of* ***colloidal size (less than 250 A***") (emphasis added). [b] US Patent 6,165,358, "Water Purifier for a Spa" (2000). Zodiac Pool Care, Inc. "*purification materials are described, for example, in U.S. Pat. No. 5,352,369*". US Patent 5,352,369, "Method of Treating Water" (1994). Fountainhead Technologies Inc.: "*the elemental silver preferably includes at least 2% of silver crystals having crystal sizes between approximately* ***3 nm*** *and* ***10 nm***" (emphasis added). [c] "*These engineered silver particles currently vary in size between about* ***10−50 nm in diameter***". (April 26, 2005) William D. Moeller, President, American Biotech Laboratories Testimony on Malaria before the U.S. House of Representatives, International Relations Committee, Subcommittee on Africa, Global Human Rights, and International Operations. [http://www.foreignaffairs.house.gov/archives/109/20915.pdf] (p.38)]. [d] SNWG "Evaluation of Hazard and Exposure Associated with Nanosilver and Other Nanometal Oxide Pesticide Products", Presentation to Scientific Advisory Panel (November 4, 2009). Docket ID: EPA-HQ-OPP-2009-0683-0165. [http://www.regulations.gov/search/Regs/contentStreamer?objectId=0900006480a52512&disposition=attachment-&contentType=pdf]. [e] Ciba Specialty Chemicals (Now BASF) "Ciba Specialty Chemicals forms marketing cooperation with Bio-Gate for silver anti-microbial technology" (December 14, 2005, Basel, Switzerland) [http://cibasc.com/index/med-index.htm?reference=41794&checkSum=C441-84952B5155A13ECC5E419C8F7310] Note figure caption "*Scanning electron microscopy showing the high porosity HyGate 4000 powder:* ***primary particle size 50−200 nm***..." (emphasis added).

achieve the registered metallic silver form,[26,30,31] in many cases with the clear intention to produce nanoscale silver. An example is given in one patent application from 1994: "*the elemental silver preferably includes at least 2% of silver crystals having crystal sizes between approximately 3 nm and 10 nm*".[31] Silver-impregnated water filters contain nano-silver particles supported on the filter matrix structure.

To verify the presence of nanoscale Ag in water filters, commercially available filters were disassembled and the carbon pellets were crushed and investigated with TEM equipped with a HAADF (High Angle Annular Dark Field) detector that is sensitive toward heavy elements (Figure 3). Details of the analysis can be found in the Supporting Information. Bright nanoparticles are visible distributed on matrix particles having sizes ranging from a few nm to about 100 nm. EDX (energy dispersive X-ray spectroscopy) analysis showed that the bright particles contain Ag whereas spectra of the light gray matrix background have no detectable Ag signal. These analyses clearly prove that during manufacturing of the silver-impregnated water filters Ag nanoparticles are formed and that all silver is present in nanoparticulate form in these filters. However, it remains to be investigated what the fate of this nanosilver is during use of the water filters, whether there is only dissolution and release of ionic silver or whether there is also release of particulate silver.

Silver-impregnated water filters have been safely used for domestic water applications such as drinking water and swimming pool filters for decades. No reports about any health or environmental effects have been reported, although the absence of such reports does not mean that no effects occurred. However, the many decades long use of these EPA registered nanosilver containing products in numerous households presents a unique opportunity for epidemiologists to investigate effects of extended use of nanosilver on human health.

Silver Algicides and Disinfectants. Silver algicides and disinfectants have been FIFRA registered as biocides since 1954. Colloidal nanosilver algicides are based on elemental silver particles maintained in a stabilized solution, containing silver in very small particle size (e.g., <100 nm). Table 2 contains some examples of currently registered biocidal products including Silver Algaedyn (EPA reg. 68161-1, Pool Products Packaging Corp), Nu-Clo Silvercide (EPA reg. 7124-101, Alden Leeds Inc.) and ASAP-AGX (EPA reg. 73499-1, American Biotech Laboratories). Figure 4 shows a TEM micrograph of Algaedyn and the size distribution of the particles determined by image analysis (>3500 particles, details of the analysis can be found in the Supporting Information), proving that Algaedyn contains silver nanoparticles with diameters between 2 and 20 nm.

It should be noted that algicide applications have been used safely in high-exposure, direct water contact, and down-the-drain applications such as swimming pool disinfection for decades without any known damaging impact on humans or the environment. The more than 50-year use of these nanosilver products presents a unique opportunity for environmental scientists to study the effects of the discharge of nanosilver into sewer systems, wastewater treatment plants, and natural waters, especially in residential areas with a lot of swimming pools. Also epidemiologists could study populations of home-owners using silver-based algicides and compare with those using other biocides to get data on a population that has been exposed to nanomaterials for decades.

SILVER NANOTOXICOLOGY

Colloidal nanosilver has been administered as a medication for almost one hundred years.[22] Regardless of the medicinal claims associated with these products a lot of research on human and animal body distribution and toxicology was carried out with these materials. One early example is a study from 1924 in which the behavior of Collargol nanosilver in the human body is described.[32] Numerous cases of the nontoxic, cosmetic condition

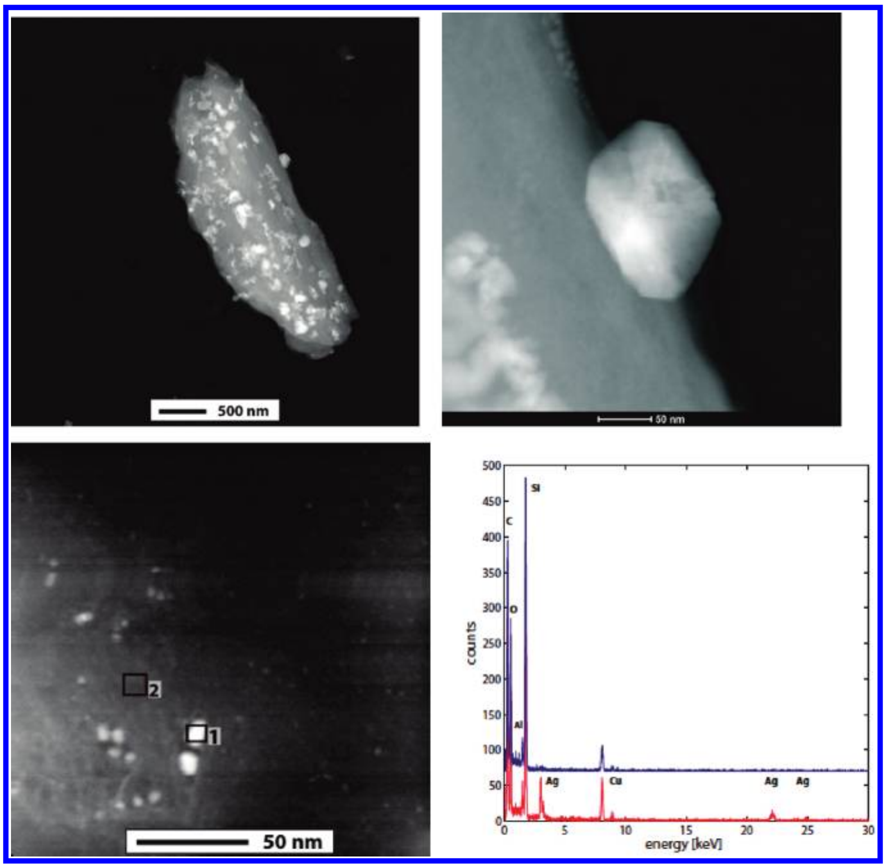

Figure 3. TEM analysis of silver-impregnated carbon filter, Zodiac Nature2 G (EPA registration no. 67712-1). Top left: larger particle with silver particles, discernible by their brightness; top right: magnification of one silver nanoparticle from the picture to the left; bottom left: small silver nanoparticles on gray matrix; bottom right: EDX spectra of the two areas in the TEM picture on the left (1: silver particles, bottom spectrum, 2: background: top spectrum). For details about methods see Supporting Information.

argyria were documented during this period. Argyria is a condition characterized by a bluish-gray discoloration of the skin.[33] The toxicity of silver is considered to be relatively low [3] and toxic effects on humans other than argyria are only observed at very high concentrations (e.g., acute oral LD50 for rats is higher than 1600 mg kg^{-1} d^{-1}).[3,33] Gaul and Staud in 1935[34] listed 43 cases of argyria of which 27 (63%) were caused by Collargol or Argyrol, thus originating from the medical use of colloidal nanosilver. The other cases were caused by silver chloride or silver iodide. A significant portion of the historical toxicological research on the effects of silver on humans can thus be considered early examples of "nanotoxicology"—predating what is currently considered to be nanotoxicology[35] by more than 80 years.

In 1939 Hill and Pillsbury[36] collected the available literature on silver and colloidal nanosilver toxicology and derived exposure limits based on the threshold value above which development of argyria can be expected. This threshold value was found to be the intake of 0.9 g of silver over the whole lifetime. The modern drinking water standard of 100 μg/L for silver is based on this value[37] and thus includes data on nanoscale-silver. Only a very few studies are available that describe toxicity of bulk silver as opposed to nanosilver or dissolved silver. However, for some standards there is a distinction between metallic and ionic silver; for instance, the American Conference of Governmental Industrial Hygienists has established separate threshold limit values for metallic silver (0.1 mg/m^3) and soluble compounds of silver (0.01 mg/m^3).[33] We can thus state that with relation to human toxicology and the legal standards related to occupational and consumer health, the toxicity of nanosilver has been taken into account and thus the existing standards are sufficient to protect consumers also from novel nanosilver, at least in forms equivalent to those available in the 1930s.

If we turn our attention to environmental risk assessment of silver we see a different picture. The data about effects of silver on environmental organisms were almost exclusively obtained using dissolved silver.[38] Most research on nonmammalian species was based on the use of dissolved silver and only recently were ecotoxicological studies with nano-Ag published, e.g., refs 8, 40, and 41. However, it has been questioned if data obtained using ionic silver should be used to derive threshold values in the environment.[42] Silver in natural waters is typically associated with the particulate and colloidal fraction[43] and is thus to some extent naturally present as nanoparticles and metal-sulfide clusters.[44] Furthermore it should be noted that the latest research indicates that under real-life environmental exposure conditions nanosilver is rapidly converted to silver sulfide, resulting in material forms that give no measurable impact on wastewater treatment plants and are much less toxic than ionic silver.[44−46] The conversion to silver sulfide highlights the importance of accounting for speciation and passivation of silver materials by ubiquitous environmental species under real-life conditions in real-world risk assessment of nanosilver materials.[5]

Because many of the aquatic species are several orders of magnitude more sensitive to silver than mammals and humans

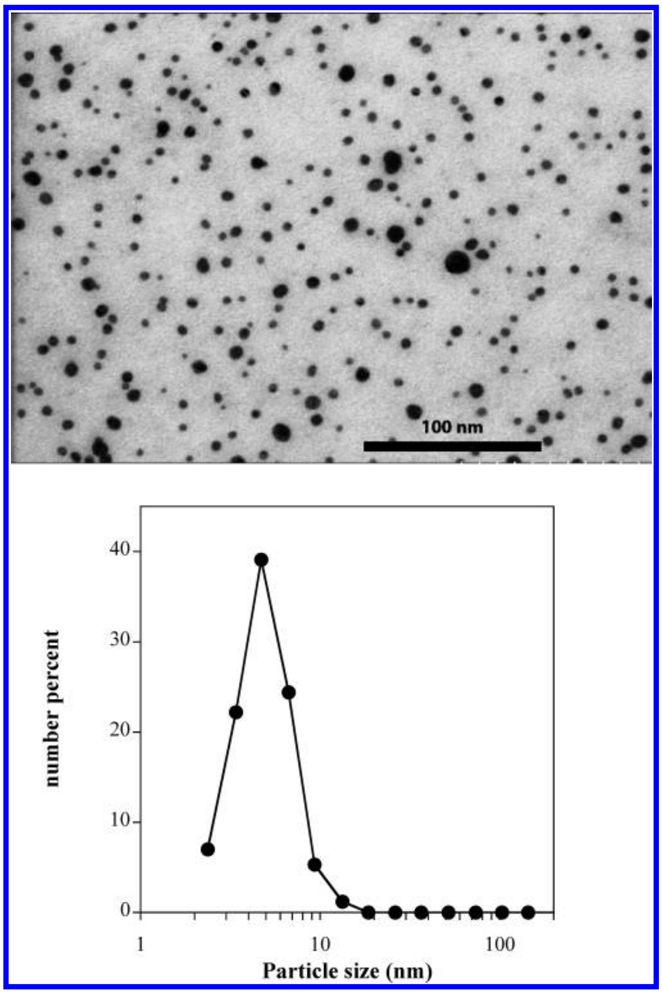

Figure 4. TEM analysis of the algicide Algaedyn (EPA registration no. 68161-1) (top) and particle size distribution by image analysis (bottom). For details about methods see Supporting Information.

(with lethal concentrations for some sensitive aquatic organisms of only 1−5 μg/L[3]), the question whether nanosilver has a different toxicity than dissolved silver is of eminent importance. However, this should be discussed in the light of the recent findings that the silver present in the environment is to a large extent present in particulate form and as nanoclusters and not as dissolved silver.

It should also be kept in mind that the expected concentrations of nanosilver in the surface waters of the U.S. are between 0.09 and 0.43 ng/L[47] whereas total silver concentrations in water were modeled to be between 40 and 320 ng/L for European surface waters.[42] Nanosilver thus contributes only a small extent to the total silver flow in the environment.

IMPLICATIONS FOR POLICY OF NANOSILVER

Regardless of what nomenclature is used, any concept of risk must ultimately derive from chemical and physical characteristics of a *specific material*. Applying the general prefix "nano" does not in itself automatically render a material harmful. Although today's nanosilver has many alternative nomenclatures and historical aliases including "colloidal silver", the underlying material is the same—extremely small particles of silver. Contrary to many common assumptions, nanosilver materials have a deep historical record of demonstrated safe use together with a long period of formal and successful regulatory oversight. The use of very high doses of colloidal nanosilver at the beginning of the 20th century has sparked a vast amount of research on the toxicology of nanosilver, resulting in the first exposure limits for silver and subsequent regulations on its use. Clearly nanosilver is a material that does not fit the paradigm of a "new" chemical with new and unknown risks. To consider otherwise is to confuse nomenclature (nano) instead of considering the material itself.

Regulators rightly state that policy needs to be made on the basis of sound science. A first principle of science is that assumptions need to be tested. For example nanosilver is assumed to be a new material because of the term "nano". However, on close inspection nanosilver materials have a long history of relatively safe and regulated use. Historical perspective also shows us that nanosilver has been intentionally manufactured and adopted commercially across a wide spectrum of everyday applications for decades. For example, EPA-registered silver nanoparticles have been safely used in down-the-drain and high-volume water-contact applications (e.g., swimming pool algicides and drinking water filter systems) bringing benefit to millions of consumers over a period of 50 years. On balance, a substantial amount is known about silver and silver nanoparticles and that historical experience of use and exposure actually points to these materials being relatively safe. While there are naturally topics where there is ample opportunity to improve scientific understanding about nanosilver (e.g., with respect to its environmental behavior and effects), it would be a mistake for regulators to ignore the accumulated knowledge of our scientific and regulatory heritage in a mistaken bid to declare nanosilver materials as new chemicals, with unknown properties and automatically harmful simply on the basis of a change in nomenclature to the term "nano". However, this does also not mean that nanosilver should be treated as harmless without testing its effect, but rather that it is sufficient to apply the already strict and coherent risk assessment framework for other silver-containing materials and products that often have a shorter history of regulated use.

ASSOCIATED CONTENT

Supporting Information. TEM analysis of water filters and TEM analysis of Algaedyn. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Nowack, B.; Bucheli, T. D. Occurrence, behavior and effects of nanoparticles in the environment. *Environ. Pollut.* **2007**, *150*, 5–22.

(2) Wiesner, M. R.; Lowry, G. V.; Jones, K. L.; Hochella, M. F.; Di Giulio, R. T.; Casman, E.; Bernhardt, E. S. Decreasing Uncertainties in Assessing Environmental Exposure, Risk, and Ecological Implications of Nanomaterials. *Environ. Sci. Technol.* **2009**, *43* (17), 6458–6462.

(3) Wijnhoven, S. W. P.; Peijnenburg, W. J. G. M.; Herberts, C. A.; Hagens, W. I.; Oomen, A. G.; Heugens, E. H. W.; Roszek, B.; Bisschops, J.; Gosens, I.; Van De Meent, D.; Dekkers, S.; De Jong, W. H.; van Zijverden, M.; Sips, A. J. A. M.; Geertsma, R. E. Nano-silver - A review of available data and knowledge gaps in human and environmental risk assessment. *Nanotoxicology* **2009**, *3* (2), 109–138.

(4) Scheringer, M.; MacLeod, M.; Behra, T.; Sigg, L.; Hungerbühler, K. Environmental risks associated with nanoparticulate silver used as biocide. *Household Pers. Care Today* **2010**, *1*, 34–37.

(5) Nowack, B. Nanosilver revisited downstream. *Science* **2010**, *330*, 1054–1055.

(6) Benn, T. M.; Westerhoff, P. Nanoparticle silver released into water from commercially available sock fabrics. *Environ. Sci. Technol.* **2008**, *42* (11), 4133–4139.

(7) Geranio, L.; Heuberger, M.; Nowack, B. Behavior of silver nano-textiles during washing. *Environ. Sci. Technol.* **2009**, *43*, 8113–8118.

(8) Navarro, E.; Piccapietra, F.; Wagner, B.; Marconi, F.; Kaegi, R.; Odzak, N.; Sigg, L.; Behra, R. Toxicity of Silver Nanoparticles to *Chlamydomonas reinhardtii*. *Environ. Sci. Technol.* **2008**, *42* (23), 8959–8964.

(9) Kaegi, R.; Sinnet, B.; Zuleeg, S.; Hagendorfer, H.; Mueller, E.; Vonbank, R.; Boller, M.; Burkhardt, M. Release of silver nanoparticles from outdoor facades. *Environ. Pollut.* **2010**, *158* (9), 2900–2905.

(10) Bell, F. A. Review of effects of silver-impregnated carbon filters on microbial water quality. *J. Am. Water Works Assoc.* **1991**, *83* (8), 74–76.

(11) Adamson, R. P.; Sommerfeld, M. R. Laboratory comparison of the effectiveness of several algicides in isolated swimming pool algae. *Appl. Environ. Microbiol.* **1980**, *39* (2), 348–353.

(12) Egger, S.; Lehmann, R. P.; Height, M. J.; Loessner, M. J.; Schuppler, M. Antimicrobial Properties of a Novel Silver-Silica Nanocomposite Material. *Appl. Environ. Microbiol.* **2009**, *75* (9), 2973–2976.

(13) Kumar, R.; Howdle, S.; Munstedt, H. Polyamide/silver antimicrobials: Effect of filler types on the silver ion release. *J. Biomed. Mater. Res. B* **2005**, *75B* (2), 311–319.

(14) Aruguete, D. M.; Hochella, M. F. Bacteria-nanoparticle interactions and their environmental implications. *Environ. Chem.* **2009**, *7* (1), 3–9.

(15) EPA. *Nanotechnology White Paper*; Report EPA 100/B-07/001; U.S. Environmental Protection Agency: Washington, DC, 2007.

(16) Gottschalk, F.; Scholz, R. W.; Nowack, B. Probabilistic material flow modeling for assessing the environmental exposure to compounds: Methodology and an application to engineered nano-TiO_2 particles. *Environ. Modeling Software* **2010**, *25*, 320–332.

(17) Lea, M. C. On allotropic forms of silver. *Am. J. Sci.* **1889**, *37*, 476–491.

(18) Frens, G.; Overbeek, J. T. Carey Leas colloidal silver. *Kolloid Z. Z. Polym.* **1969**, *233* (1−2), 922–&.

(19) Henglein, A.; Giersig, M. Formation of colloidal silver nanoparticles: Capping action of citrate. *J. Phys. Chem. B* **1999**, *103* (44), 9533–9539.

(20) Dong, X. Y.; Ji, X. H.; Wu, H. L.; Zhao, L. L.; Li, J.; Yang, W. S. Shape Control of Silver Nanoparticles by Stepwise Citrate Reduction. *J. Phys. Chem. C* **2009**, *113* (16), 6573–6576.

(21) Paal, C. Über colloidales Silber. *Ber. Dtsch. Chem. Ges.* **1902**, *35* (2), 2224–2236.

(22) Boese, K. Über Collargol, seine Anwendung und seine Erfolge in der Chirurgie und Gynäkologie. *Dtsch. Z. Chir.* **1921**, *163* (1−2), 62–84.

(23) Bogdanchikova, N. E.; Kurbatov, A. V.; Tret'yakov, V. V.; Rodionov, P. P. Activity of colloidal silver preparations towards smallpox virus. *Pharm. Chem. J.* **1992**, *26* (9−10), 778–779.

(24) Bechhold, H. Die Gallertfiltration. *Z. Chem. Ind. Kolloide* **1907**, *2*, 3−9–33−41.

(25) Moudry, Z. V. *Process of producing oligodynamic metal biocides*. United States Patent 2,927,052, 1953.

(26) Manes, M. *Silver impregnated carbon*. United States Patent 3,374,608, 1968.

(27) Fung, M. C.; Bowen, D. L. Silver Products for Medical Indications: Risk-Benefit Assessment. *Clin. Toxicol.* **1996**, *34* (1), 119–126.

(28) Kasemo, B.; Johansson, S.; Persson, H.; Thormählen, P.; Zhdanov, V. P. Catalysis in the nm-regime: Manufacturing of supported model catalysts and theoretical studies of the reaction kinetics. *Top. Catal.* **2000**, *13*, 45–53.

(29) Ryu, S. K.; Eom, S. Y.; Cho, T. H.; Edie, D. D. Distribution of Silver Particles in Silver-containing Activated Carbon Fibers. *Carbon Sci.* **2003**, *4* (4), 168–174.

(30) Kumar, V. S.; Nagaraja, B. M.; Shashikala, V.; Padmasri, A. H.; Madhavendra, S. S.; Raju, B. D.; Rao, K. S. R. Highly efficient Ag/C catalyst prepared by electro-chemical deposition method in controlling microorganisms in water. *J. Mol. Catal A: Chem.* **2004**, *223* (1−2), 313–319.

(31) Heinig, C. F. *Method of treating water*. United States Patent 5,352,369, 1994.

(32) Schlee, H.; Zweifel, E. Über das Verhalten von Silberpräparaten, insbesondere von Kollargol im Organismus. *Z. Hyg. Infekt.* **1924**, *102*, 454–460.

(33) Drake, P. L.; Hazelwood, K. J. Exposure-Related Health Effects of Silver and Silver Compounds: A Review. *Ann. Occup. Hyg.* **2005**, *49* (7), 575–588.

(34) Gaul, L. E.; Staud, A. H. Seventy cases of generalized argyria following organic and colloidal silver medication, including biospectrometric analysis of ten cases. *J. Am. Med. Assoc.* **1935**, *104* (16), 1387–1390.

(35) Oberdörster, G.; Oberdörster, E.; Oberdörster, J. Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. *Environ. Health Perspect.* **2005**, *113* (7), 823–839.

(36) Hill, W. R.; Pillsbury, D. M. *Argyria, the Pharmacology of Silver*; The Williams & Wilkins Co.: Baltimore, MD, 1939.

(37) Purcell, T. W.; Peters, J. J. Historical impacts of environmental regulation of silver. *Environ. Toxicol. Chem.* **1999**, *18* (1), 3–8.

(38) EPA. Registration eligibility document Silver, List D, Case 4082; U.S. Environmental Protection Agency: Washington, DC, 1992.

(39) Shouse, S. S.; Whipple, G. H. Effects of intravenous injection of colloidal silver upon the hematopoietic system in dogs. *J. Exp. Med.* **1931**, *53* (3), 413–420.

(40) Lee, K. J.; Nallathamby, P. D.; Browning, L. M.; Osgood, C. J.; Xu, X. H. N. In vivo imaging of transport and biocompatibility of single silver nanoparticles in early development of zebrafish embryos. *ACS Nano* **2007**, *1* (2), 133–143.

(41) Choi, O.; Hu, Z. Q. Size dependent and reactive oxygen species related nanosilver toxicity to nitrifying bacteria. *Environ. Sci. Technol.* **2008**, *42* (12), 4583–4588.

(42) Blaser, S. A.; Scheringer, M.; MacLeod, M.; Hungerbuhler, K. Estimation of cumulative aquatic exposure and risk due to silver: Contribution of nano-functionalized plastics and textiles. *Sci. Total Environ.* **2008**, *390* (2−3), 396–409.

(43) Shafer, M. M.; Overdier, J. T.; Armstong, D. E. Removal, partitioning, and fate of silver and other metals in wastewater treatment plants and effluent-receiving streams. *Environ. Toxicol. Chem.* **1998**, *17* (4), 630–641.

(44) Luther, G. W.; Rickard, D. T. Metal sulfide cluster complexes and their biogeochemical importance in the environment. *J. Nanopart. Res.* **2005**, *7* (4−5), 389–407.

(45) Choi, O.; Cleuenger, T. E.; Deng, B. L.; Surampalli, R. Y.; Ross, L.; Hu, Z. Q. Role of sulfide and ligand strength in controlling nanosilver toxicity. *Water Res.* **2009**, *43* (7), 1879–1886.

(46) Kim, B.; Park, C.-S.; Murayama, M.; Hochella, M. F. Discovery and Characterization of Silver Sulfide Nanoparticles in Final Sewage Sludge Products. *Environ. Sci. Technol.* **2010**, *44*, 7509–7514.

(47) Gottschalk, F.; Sonderer, T.; Scholz, R. W.; Nowack, B. Modeled environmental concentrations of engineered nanomaterials (TiO_2, ZnO, Ag, CNT, fullerenes) for different regions. *Environ. Sci. Technol.* **2009**, *43*, 9216–9222.