Many antimicrobial technologies are available for textiles. They may be used in many different textile applications to prevent the growth of microorganisms. Due to the biological activity of the antimicrobial compounds, the assessment of the safety of these substances is an ongoing subject of research and regulatory scrutiny. This review aims to give an overview on the main compounds used today for antimicrobial textile functionalization. Based on an evaluation of scientific publications, market data as well as regulatory documents, the potential effects of antimicrobials on the environment and on human health were considered and also life cycle perspectives were taken into account. The characteristics of each compound were summarized according to technical, environmental and human health criteria. Triclosan, silane quaternary ammonium compounds, zinc pyrithione and silver-based compounds are the main antimicrobials used in textiles. The synthetic organic compounds dominate the antimicrobials market on a weight basis. On the technical side the application rates of the antimicrobials used to functionalize a textile product are an important parameter with treatments requiring lower dosage rates offering clear benefits in terms of less active substance required to achieve the functionality. The durability of the antimicrobial treatment has a strong influence on the potential for release and subsequent environmental effects. In terms of environmental criteria, all compounds were rated similarly in effective removal in wastewater treatment processes. The extent of published information about environmental behavior for each compound varies, limiting the possibility for an in-depth comparison of all textile-relevant parameters across the antimicrobials. Nevertheless the comparative evaluation showed that each antimicrobial technology has specific risks and benefits that should be taken into account in evaluating the suitability of different antimicrobial products. The results also indicated that nanoscale silver and silver salts that achieve functionality with very low application rates offer clear potential benefits for textile use. The regular care of textiles consumes lots of resources (e.g. water, energy, chemicals) and antimicrobial treatments can play a role in reducing the frequency and/or intensity of laundering which can give potential for significant resource savings and associated impact on the environment.
Textiles are ubiquitous and are used throughout the world for various purposes every day. In 2008, the world per capita fiber consumption was 10.4 kg (FAO and ICAC, 2011). A portion of the textiles that are consumed today are treated with biocides that prevent or inhibit the growth of microorganisms. Biocides are used either to protect the textile from the effects of microbial growth or to protect the user from harmful microorganisms (Hund-Rinke et al., 2008). For biocidal textile treatment, mostly antimicrobials are used which, in contrast to the more general term biocides, exclude other biocide types such as herbicides, insecticides and rodenticides. Textiles treated with antimicrobials are not a recent phenomenon and have been present in the marketplace for decades. The current uses of antimicrobial textiles range from outdoor applications such as tents, tarpaulins, awnings, blinds, parasols, sails and waterproof clothing to indoor applications such as shower curtains and mattress ticking (Lacasse and Baumann, 2004). They are also used in some consumer textiles such as sports wear, T-shirts and socks and also in medical settings for instance in bedding (Hoefler, 2006). In 2000, an estimated 100 thousand metric tonnes of antimicrobial fibers were produced (Gao and Cranston, 2008).

Many different compounds are used to impart antimicrobial functionality to textiles, ranging from synthetic organic compounds such as triclosan, quaternary ammonium compounds, polybiquianides, N-halamines through to metals such as silver and naturally derived antimicrobials such as chitosan (Gao and Cranston, 2008; Purwar and N-halamines through to metals such as silver and naturally derived antimicrobials such as chitosan (Gao and Cranston, 2008; Purwar and

Antimicrobials for textiles need to fulfill many different criteria including efficacy against microorganisms, suitability for textile processing, durability, and a favorable safety and environmental profile (Gao and Cranston, 2008). The development of new and better antimicrobials is an ongoing topic of research (Bshena et al., 2011; Dastjerdi and Montazer, 2010) and antimicrobials based on naturally-derived products are increasingly discussed (Joshi et al., 2009). A survey by the European Commission (European Commission, 2009) listed the consumption of biocidal substances in Europe as 1546 metric tonnes for use in textiles and the potential for transfer from fabric surfaces (Heine et al., 2007). There are many strategies for addressing the care and
benz-isothiazolinone (BIT), 10,10(Silvestry-Rodriguez et al., 2007) and Ag+ ions disrupting normal Ca2+ or Zn2+ (Schierholz et al., 1998) leading to cell death. The bactericidal effect of ZnPT derives from its ability to disrupt membrane transport of Zn2+ (Maris, 1995). Si-QACs irreversibly bind to the phospholipids and proteins of the membrane, thereby impairing membrane permeability (Maris, 1995). The bactericidal efficacy of silver is caused by multiple mechanisms including the strong binding of Ag+ with disulfide (S–S) and sulfhydryl (–SH) groups found in the proteins of microbial cell walls, (Silvestry-Rodriguez et al., 2007) and Ag+ ions disrupting normal metabolic processes by displacement of essential metal ions such as Ca2+ or Zn2+ (Schierholz et al., 1998) leading to cell death.

2.2. Textile products that use antimicrobials

Requirements for antimicrobial treatments differ according to the end use of a textile product. The human toxicity profile is important for skin-contact garments, while the photostability of the antimicrobial substance is important in the case of outdoor textiles. The strengths and weaknesses of the antimicrobials discussed here (Ag, TCS, Si-QAC and ZnPT) as well as the end-use requirements that are placed on a substance are reflected in the use pattern of the antimicrobial for different applications within the textile sector. Ag, TCS and Si-QAC are commonly used for apparel textiles and Ag and Si-QAC are also widely used in the medical field (Table 2). ZnPT is often favored for non-skin contact uses such as mattresses or bedding. Other synthetic organic antimicrobials such as n-octyl-isothiazolinone (OIT), benz-isothiazolinone (BIT) or 10,10′-oxybisphenoarsine (OBPA) are often limited to non-skin contact textile coatings.

3. Production of antimicrobials

The volume of antimicrobials in the marketplace today ranges from high volume compounds to materials produced only in small volumes. The most prevalent antimicrobials for textile use include metals and metal salts such as silver, quaternary ammonium compounds (QAC), halogenated phenols such as trichlosan, metal–organic complexes such as zinc pyrithione, polybiuretanes such as polyetheramethylene biguanides (PHMB) and N-halamine compounds (Gao and Cranston, 2008; Heine et al., 2007; Joshi et al., 2009; Purwar and Joshi, 2004; Simoncic and Tomsic, 2010). In terms of volumes, QAC, phenols, organo-metal compounds, biguanides and silver are the most dominant compounds (Fig. 1). Fig. 1 also shows that in 2004 silver was responsible for treating a 9% market share of antimicrobial textiles while in 2011 this share had increased to an estimated 25%, indicating that while a larger proportion of the textile volume were treated with silver, silver replaced synthetic organic compounds (hereinafter referred to as organic compounds) that would otherwise have been used...
in significantly higher quantities. The relative market volumes of antimicrobial consumption in textiles according to market information are as follows (from high to low): QAC > phenolics > TCS > ZnPT > PHMB > OIT > tolysulfone > TCMTB > DCOIT > sodium pyrithione > silver (Bl, 2004). Literature sources and market data indicate that Ag, TCS, Si-QAC and ZnPT belong to the most prevalent antimicrobials on the market today and these four classes of substances were chosen as the focus of the present review. In the subsequent sections these compounds are described in detail and antimicrobial production data is presented.

### 3.1. Silver

Silver is an important metal in manufacturing processes and in many different end products due to its unique properties including its electrical and thermal conductivity, its optical reflectivity and its antimicrobial effect (Silver Institute, 2011a). A yearly survey commissioned by the Silver Institute (Silver Institute, 2011b) reported a global demand of 27,333 metric tonnes in 2010. Hund-Rinke et al. (2008) estimated the market share of all Ag uses, including bical Ag applications, based on data of the Silver Institute and a survey of silver suppliers. Most of the global consumption was attributed to industrial applications (38.2%), and smaller percentages were attributed to the investment sector (1.9%) and manufacture of coins and medals (3.1%). Industrial applications accounted for less than 0.5% of the Ag supply — equating to approximately 140 metric tonnes in total. The share of bical Ag compared to all Ag applications in Hund-Rinke et al. (2008) was adapted by Burkhardt et al. (2011) which listed a share of bical Ag of 0.2–0.5% (56–140 metric tonnes). Another estimate by The Silver Institute (2011a) outlined new emerging uses of Ag and nano-Ag, and revealed a total bical Ag consumption of 129 metric tonnes in 2010 (Table 3). From data on different Ag forms used in textiles in Europe (Burkhardt et al., 2011) and on bical Ag use in the United States (USEPA, 2011) two more estimates for the global bical Ag consumption were derived by a population-adjusted extrapolation of the regional data relative to the bical Ag consumption in the OECD countries. The extrapolation resulted in a global bical Ag consumption of 29 and 85 metric tonnes. Applications of these 29 to 140 metric tonnes of bical Ag include many uses including water treatment, detergents and softeners, paints and finishes, plastics, medical applications, sanitary facilities and also fibers and textiles (Hund-Rinke et al., 2008). Two decades ago it was estimated that >90% of bical Ag was used for water filters and 3% as algaecides (USEPA, 1992). A more recent estimate for average global consumption stated that 68% of bical Ag is used for water treatment and 32% for other uses (Silver Institute, 2005a). If we take a highly conservative assumption that the 32% of ‘‘other’’ bical Ag was used for textiles, this would equate to 45 metric tonnes bical Ag used in textile applications globally (Table 2). In 2004, quantitative market data showed a lower value of 3.5 metric tonnes consumed in textiles (Bl, 2004). Given the conservative assumption for the current estimate the actual bical Ag consumption in textiles is likely to be at the lower end of the given range, even if accounting for the fact that the popularity of antimicrobial silver applications has been increasing in the last decade.

Biocidal Ag includes different Ag forms that act as sources of silver ions (Ag+) which ultimately provide the antimicrobial effect. There are three main groups of commercially available silver antimicrobials: silver ion exchangers, silver salts and silver metal (Burkhardt et al., 2011). Silver ion exchangers include silver zirconium phosphates, silver zeolites and silver glasses. Silver salts include silver chloride (AgCl), nanosilver chloride and silver chloride microcomposites. Silver chloride microcomposites are composed of AgCl nanoparticles attached to titanium dioxide as carrier material (Burkhardt et al., 2011; Kulthong et al., 2010). Metallic silver materials include silver metal filaments and electrolytically coated fibers, nanosilver metal and silver metal microcomposites. Market data derived from manufacturer surveys in Europe indicated that silver salts (including nanosilver chloride) are the most widely used form of Ag in textiles accounting for 79% (Burkhardt et al., 2011) while metallic Ag and silver ion exchangers are responsible for 13% and 8% of silver use in textiles respectively (Fig. 2). This data does not distinguish between silver salts in the nanorange and bulk silver salts. Even though the

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### Table 3

<table>
<thead>
<tr>
<th>Reference or data source</th>
<th>Estimate description</th>
<th>Global biocidal Ag consumption [metric tonnes]</th>
<th>Share of biocidal Ag in total global Ag demand [%]</th>
<th>Global max. bical Ag used in textiles [metric tonnes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hund-Rinke et al. (2008)</td>
<td>Top-down</td>
<td>140</td>
<td>0.5</td>
<td>45</td>
</tr>
<tr>
<td>Silver Institute (2011a)</td>
<td>Top-down</td>
<td>129</td>
<td>0.5</td>
<td>42</td>
</tr>
<tr>
<td>USEPA (2011)</td>
<td>Bottom-up</td>
<td>85</td>
<td>0.3</td>
<td>27</td>
</tr>
<tr>
<td>Burkhardt et al. (2011)</td>
<td>Top-down</td>
<td>56</td>
<td>0.2</td>
<td>18</td>
</tr>
<tr>
<td>Burkhardt et al. (2011)</td>
<td>Bottom-up</td>
<td>29</td>
<td>0.1</td>
<td>9</td>
</tr>
</tbody>
</table>

---

a The top-down approach estimates the bical Ag consumption in textiles on the basis of data on global bical Ag consumption in all uses and the bottom-up approach estimates the global bical Ag consumption in textiles based on regional data of Ag used in textile applications and also derives an extrapolated value for the global bical Ag consumption in all applications.

b Based on a global silver consumption (all uses) of 27,333 metric tonnes in 2010 (Silver Institute, 2011b).

c The separation between of bical Ag for water treatment and for other uses (maximally used in textiles) is based on data of the Silver Institute (2005a).

d The bical Ag consumption in textiles was extrapolated from the Ag used as material preservative in the United States and the population number of the OECD member countries.

e The bical Ag consumption in textiles was extrapolated from data about different Ag forms produced for textiles in Europe and the population number of the OECD member countries.

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Fig. 2. Ag consumption for all uses (left), bical Ag uses (middle) and Ag forms used in textiles (right). Data are from Hund-Rinke et al. (2008), Silver Institute (2005a) and Burkhardt et al. (2011).
term “nanosilver” is conventionally attributed to silver metals, also a fraction of the silver salts falls under the nanoparticle definition by the International Standard Organisation which defines a nanoparticle as having three dimensions in the nanoscale between 1 and 100 nm (ISO, 2010). Taking this into account, between 13 and 79% of all Ag in textiles (9–45 metric tonnes) may be in the nanoform, corresponding to 1.2–36 metric tonnes globally. To validate this, we used additional data to derive an independent estimate on how much nano-Ag is used in textiles. Data on nano-Ag consumption was extrapolated proportionally to the population of the OECD member countries. This calculation revealed a global nano-Ag consumption of 53 metric tonnes based on data on nano-Ag production in the United States, Japan and Europe (Scheringer et al., 2010), a production of 11 to 80 metric tonnes based on data from the United States (Hendren et al., 2011) and to a production of 13 to 55 metric tonnes based on production data in Europe (Piccinno et al., 2012). According to Piccinno (Piccinno et al., 2012) the share of total nano-Ag used in textiles applications ranges from 30 to 50%, which equals a total nano-Ag volume used in textiles of 3.4–40 metric tonnes per year. This corresponds well to the range of nano-Ag production provided on the basis of the different Ag forms used in textiles (1.2–36 metric tonnes) however it is considered likely that the actual volume is at the lower end of this range.

3.2. Triclosan

Triclosan (2,4,4′-trichloro-2′-hydroxydiphenyl ether), belonging to the chlorinated phenolic compounds, is applied in a variety of products as an antimicrobial and preservative (Dann and Hontela, 2011). It is widely used in disinfectants, soaps, toothpastes, textiles, and personal care products such as shampoos and deodorants (Dann and Hontela, 2011). TCS has a worldwide production of 1500 metric tonnes (Bester, 2005) with 350 metric tonnes produced in Europe (Singer et al., 2002) and 450 metric tonnes in the USA (von der Ohe et al., 2011). These production volumes are consistent with Dye et al. (2007) where annual production and import volumes of TCS were reported in the order of 10 to 1000 metric tonnes for the EU. The Scientific Committee on Consumer Safety (SCCS, 2010) estimated an annual consumption of 450 metric tonnes within the EU.

TCS is primarily used in the personal care sector (NICNAS, 2009; SCCS, 2010). In Australia up to 49% of TCS is used in personal care products and cosmetics (NICNAS, 2009) and in the EU 85% is used in personal care products, 10% for food contact materials and only 5% is used in textiles (SCCS, 2010). Assuming that 5% of global consumption (1500 metric tonnes) was used in textile manufacture, this would indicate that 75 metric tonnes are used worldwide for textile treatment. In 2004 the TCS consumption in textiles was 210 metric tonnes according to market information (BI, 2004), which corresponds to 15% of the global TCS production. A small proportion of global TCS consumption (5 to 15%) is hence applied in the textile industry with other sectors using a higher proportion. At 1500 metric tonnes the total TCS production is several times higher than the global production of biocidal Ag (29–140 metric tonnes). TCS consumption in textiles (75–210 metric tonnes) is at least twice as high as the consumption of biocidal Ag in textiles (9–45 metric tonnes).

### 3.3. Silane quaternary ammonium compounds

Quaternary ammonium compounds are a chemical class of cationic surface active agents (Simonic and Tomsic, 2010). In textile manufacturing they are used as biocides and also as auxiliaries at different stages of the manufacturing process, e.g. during pretreatment, for coloring and finishing, as conditioning, antistatic or softening agents and as detergents (KEMI, 1997; Lacasse and Baumann, 2004). Due to their antimicrobial properties QAC are also used as surface disinfectants in the food sector and in the medical field (Mullen, 2002), in plant protection products and pharmaceuticals (Uhl et al., 2005). QAC represent a diverse and large group of compounds with 191 compounds listed in the PAN Pesticides Database (PAN, 2012). Conventionally the term QAC refers to the subgroup of linear alkyl ammonium compounds (Most, 2007) that are composed of a hydrophobic alkyl chain and a hydrophilic counterpart (Uhl et al., 2005). For antimicrobial textile treatments mainly the compounds containing long alkyl chains (12–18 carbon atoms) have been used (Purwar and Joshi, 2004). The dominant compound that is considered in this review, is a linear alkyl ammonium QAC based on silane quaternary ammonium compounds.

Information about QAC and Si-QAC consumption in textiles is limited in the scientific literature. Uhl et al. (2005) reported a global consumption of cationic and amphoteratic surfactants of 1.16 million metric tonnes and stated that the largest share is consumed as fabric softeners, in toiletries and as textile auxiliaries. According to Wahle and Falkowski (2002) only 4% of cationic surfactants is used for biocidal purposes and Seidel (2007) gives a QAC production in the United States

### Table 4

<table>
<thead>
<tr>
<th>Antimicrobial</th>
<th>Antimicrobial content [mg/kg textile]</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag (all forms)</td>
<td>0.016–10,300</td>
<td>Experimental analysis of sixteen consumer products (sport shirts, underwear, shower curtain, socks, top mattress etc.)</td>
<td>DEPA (2012)</td>
</tr>
<tr>
<td></td>
<td>1.5–2925</td>
<td>Experimental analysis of seven consumer products (socks, shirts, trousers)</td>
<td>Lorenz et al., 2012</td>
</tr>
<tr>
<td></td>
<td>0.4–1360</td>
<td>Experimental analysis of sixteen consumer products (socks, underwear, shirts, buff, wipe, pajama, children body)</td>
<td>KEMI (2012)</td>
</tr>
<tr>
<td></td>
<td>30–270</td>
<td>Experimental analysis of three consumer products (shirt, teddy bear, towel)</td>
<td>Benn et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>230,000/270,000</td>
<td>Experimental analysis of two medical products (mask and cloth) (likely containing silver metal wires)</td>
<td>Benn et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>0.99–15.16</td>
<td>Experimental analysis of three commercially available shirts</td>
<td>Kulthong et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>2660/21,600</td>
<td>Experimental analysis of two commercially available socks (likely containing metallic silver fibers)</td>
<td>Geranio et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>2.8–1310</td>
<td>Experimental analysis of four products (socks, shirts)</td>
<td>GSM (2009)</td>
</tr>
<tr>
<td></td>
<td>0.9–1358</td>
<td>Experimental analysis of five commercially available socks</td>
<td>Benn and Westerhoff (2008)</td>
</tr>
<tr>
<td>TCS</td>
<td>48.9/50.7</td>
<td>Experimental analysis of two consumer products (shorts and socks) that contained a mixture of triclosan and triclocarban (the triclocarban concentration in those two textiles was 3.5/4.5 mg/kg)</td>
<td>KEMI (2012)</td>
</tr>
<tr>
<td></td>
<td>167</td>
<td>Concentration assumed for life cycle assessment based on considered literature</td>
<td>Walser et al. (2011)</td>
</tr>
<tr>
<td>Si-QAC</td>
<td>7–195</td>
<td>Experimental analysis of five antimicrobial products (underwear, shorts, sandals)</td>
<td>Rastogi et al., 2003</td>
</tr>
<tr>
<td>ZnPT</td>
<td>2500</td>
<td>Recommended application rate of a silane quaternary ammonium compounds</td>
<td>BI (2004)</td>
</tr>
<tr>
<td></td>
<td>600–2000</td>
<td>Concentration achieved in the finishing of textile samples to determine wash durability of equipped textiles</td>
<td>Morris and Welch (1983)</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>Maximal recommended application rate in a product registration document</td>
<td>USEPA (2008a)</td>
</tr>
</tbody>
</table>
of 344 thousand metric tonnes mostly for consumer products. Market information however provided consumption data on biocidal QAC in textiles and listed a global QAC consumption in textiles of 1128 metric tonnes in 2004, most of it being a particular type of Si-QAC, 3-(trimethoxysilyl) propyl dimethyl octadecyl ammonium chloride (Bl, 2004). Compared to the total volume of QAC consumption in all forms of consumer products this is a very low amount. Nevertheless Si-QAC seems to have the largest consumption volume as textile antimicrobial compared to the consumption volumes of TCS and Ag.

3.4. Zinc pyrithione

Zinc pyrithione is a metallo-organic broad spectrum antimicrobial that acts against the growth of bacteria, fungi, algae and mildew (Ranke and Jastorff, 2000; USEPA, 2004). The antimicrobial property of zinc pyrithione is used in many different end products. For decades the compound has been used in particular as a fungicide in anti-dandruff shampoos (Lacasse and Baumann, 2004). ZnPT is also well known as an antifouling agent for ship vessels (Thomas and Brooks, 2010) where it was introduced to replace tin compounds. Nano-Ag is also considered coated fibers and unspecified Ag forms and also included a number of zeolites, glasses and phosphate complexes. For the data analysis, the silver zeolites were combined with the silver zeolites listed under PC code 221700, and the phosphates and glasses were excluded. Since also silver products registered as “nano-Ag” can be composed of metallic Ag particles, the category “metallic silver” was retitled as “bulk Ag”.

For each antimicrobial substance, between 1 and 22 product registrations that provided recommended application rates for textiles were included. The recommended concentrations of the active substance are usually given as mass of active per dry weight of textile (mg/kg textile or ppm). In some product registrations it was distinguished between application rates for different textile uses (e.g. apparel vs. mattresses) or different incorporation methods (topical and the application procedure (bulk incorporation vs. topical treatment). In order to examine the application rates of textile products treated with Ag, TCS, Si-QAC and ZnPT, an analysis of antimicrobial product registrations in the United States was conducted. Manufacturer recommended antimicrobial application rates for textiles, listed in the corresponding product registration labels, were extracted from the National Pesticide Information Retrieval System (NPIRS, 2012). The NPIRS was searched for the following Ag forms and organic compounds chosen on the basis of the categories and corresponding PC codes given in the PAN Pesticides Database (PAN, 2012): Metallic silver (PC code: 72501), nano-Ag (PC code: 72599), silver chloride (PC code: 72506), silver zeolite (PC code: 221700), TCS (PC code: 54901), different Si-QAC types (PC codes: 107401, 107403, 107409 and 169160) and ZnPT (PC code: 88002). Most registrations in the category “metallic silver” concerned coated fibers and unspecified Ag forms and also included a number of zeolites, glasses and phosphate complexes. For the data analysis, the silver zeolites were combined with the silver zeolites listed under PC code 221700, and the phosphates and glasses were excluded. Since also silver products registered as “nano-Ag” can be composed of metallic Ag particles, the category “metallic silver” was retitled as “bulk Ag”.

4. Antimicrobial application on textiles

4.1. Application rate

One of the factors that influences the antimicrobial activity of biocidal substances is the application concentration (Maillard, 2005). The antimicrobial concentration in a textile product (application rate) which is required to exert the antimicrobial effect depends on the type of antimicrobial, the intended purpose of the treated product (e.g. medical vs. general apparel), the fabric construction, the fixation of the antimicrobial to the textile and stability during use (durability) and the application procedure (bulk incorporation vs. topical treatment). In order to examine the application rates of textile products treated with Ag, TCS, Si-QAC and ZnPT, an analysis of antimicrobial product registrations in the United States was conducted. Manufacturer recommended antimicrobial application rates for textiles, listed in the corresponding product registration labels, were extracted from the National Pesticide Information Retrieval System (NPIRS, 2012). The NPIRS was searched for the following Ag forms and organic compounds chosen on the basis of the categories and corresponding PC codes given in the PAN Pesticides Database (PAN, 2012): Metallic silver (PC code: 72501), nano-Ag (PC code: 72599), silver chloride (PC code: 72506), silver zeolite (PC code: 221700), TCS (PC code: 54901), different Si-QAC types (PC codes: 107401, 107403, 107409 and 169160) and ZnPT (PC code: 88002). Most registrations in the category “metallic silver” concerned coated fibers and unspecified Ag forms and also included a number of zeolites, glasses and phosphate complexes. For the data analysis, the silver zeolites were combined with the silver zeolites listed under PC code 221700, and the phosphates and glasses were excluded. Since also silver products registered as “nano-Ag” can be composed of metallic Ag particles, the category “metallic silver” was retitled as “bulk Ag”.

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application or incorporation into synthetic fibers) and in others only a more general recommendation of possible application rates was given. In order to obtain an average application rate for each antimicrobial type, some of the input data was further processed. If a range of possible application rates for textiles was given, all values within this range were included in the dataset as single data points. If a maximal and a minimal value were given, all data points in between were considered. If only a maximal application rate was given, Monte Carlo calculations were used to generate random data points that were uniformly distributed below this maximum value. For each compound a different number of data points was generated by Monte Carlo calculations. The number of data points generated for a particular compound was equal to the maximum number of data points in the remaining product registrations of the same compound. These calculations were carried out by using the statistical software environment R (R Development Core Team, 2008).

The analysis results, presented as medians with the 25/75% quantiles, show that the recommended application rates cover a broad range (Fig. 3). The smallest recommended application rate (on a weight basis) was found for the category nano-Ag with a range of 10 to 100 mg/kg (median: 55 mg/kg). The highest application rate was found for bulk Ag (e.g. silver coated fibers) with a maximum of 40000 mg/kg and a median of 12990 mg/kg. Application rates for the organic compounds were as follows (from high to low): TCS > QAC > ZnPT, with medians of 6426 mg/kg, 5439 mg/kg and 3263 mg/kg respectively (Table 5). The application rates of silver chloride (median 753 mg/kg) and silver zeolite (median 617 mg/kg) were between the levels of nano-Ag and the organic compounds.

The application rates given in the product registrations are recommendation ranges and do not necessarily reflect the actual application rates found in textile products on the market. Therefore data about the antimicrobial concentration in textile products was additionally compiled from literature (Table 4). The measured range of Ag in a selection of Ag containing products was between 0.016 and 270,000 mg/kg. The maximum value was found in a medical mask which, given the very high concentration, presumably contained silver metal wires. The smallest measured TCS concentration in a selection of articles was 7 mg/kg and the highest measured TCS concentration was 195 mg/kg. The literature values of Ag contents correspond reasonably well with the recommended concentrations in Fig. 3, but it should be noted that the measured TCS contents are a lot lower than the recommended application rates. This might be because the recommended application rates in Fig. 3 apply to a broad range of different textile products, while the experimentally determined concentrations in literature apply to specific antimicrobial products. Experimentally determined antimicrobial concentrations were reported only for Ag and TCS. For Si-QAC a product recommendation suggested an application rate of 2500 mg/kg. Concentrations for ZnPT used to treat textiles and applications levels as indicated by USEPA ranged from 600 to 2000 mg/kg.

4.2. Durability

Durability of antimicrobial textile treatments is fundamental to ensuring that the treated textile maintains its biocidal performance throughout its life cycle. Washing and wear of the textile can lead to a progressive loss of the antimicrobial, primarily due to dissolution of the active substance and/or mechanical damage to the fabric or treated surface. Progressive loss of the antimicrobial can continue until the concentration of the active falls below the inhibitory concentration, at which point the textile can no longer reliably fulfill its antimicrobial function. For many textile applications the wash durability is a key parameter for assessing the performance of antimicrobial treatments. Sun and Worley (2005) state that a durable antimicrobial textile finish should survive at least 50 machine washes which is a figure in line with industrial practices. It is a routine part of the industrial assessment of antimicrobial treatments in practice to perform activity testing on the initial unwashed textile and also after a series of washes. Treatments that achieve highest wash durability with the lowest application rate (active concentration) are generally favored in the marketplace, so there is a strong tendency towards adoption of the most efficient and highest performing treatments. Results from routine durability tests from industry are generally not available in scientific literature, nevertheless there are some studies that addressed either the leaching of Ag (Benn and Westerhoff, 2008; Benn et al., 2010; Geranio et al., 2009; Lorenz et al., 2012), the leaching of TCS (KEMI, 2012; Orhan et al., 2007), the leaching of Si-QAC (Kirimian Erdem and Sanli Yurudu, 2008) or the leaching of ZnPT (USEPA, 2008a) from textiles. From this literature data it is however not possible to determine the relative durability of the different substances because durability is influenced by many different factors. The range of different study designs and textile substrates makes the task of compiling a comprehensive comparison of the durability of different antimicrobial textiles very difficult. If consumer products are used to assess the durability, there is little information available about the application procedure used to treat the textile. For instance, the active ingredient may be added in different stages of the textile manufacturing process, either during spinning of synthetic fibers or it can be applied topically in the final textile finishing stage (Gao and Cranstom, 2008). In any case a strong fixation of the antimicrobial to the textile is desirable to improve the durability of the antimicrobial (Pappaspyrides et al., 2008). As discussed in Section 4.1, antimicrobial treatments typically have a range of recommended application rates (Fig. 3) that reflect how much of the active is required to offer competitive performance (including wash durability) and so these values illustrate the trade-off between concentration and durability for the various active substances.

5. Environmental and health profile

5.1. Behavior in the environment

The behavior of a substance in the environment is determined through different characteristics that can serve as measures to assess the environmental exposure and hazard of antimicrobial compounds. A selection of the most important compound characteristics that are taken as a basis to compare Ag, TCS, Si-QAC and ZnPT is presented in this section.

If antimicrobials are released from textiles, they may eventually end up in the aquatic environment if they are not removed in the wastewater treatment. Various studies have revealed that large fractions of Ag, nano-Ag and TCS are effectively removed during wastewater treatment, namely 85 – 99% for Ag (Blaser et al., 2008), >95% for AgCl (Burkhardt et al., 2010) and metallic nano-Ag (Keegi et al., 2011) and 90–96% for TCS (Dann and Hontela, 2011). Besides removal through sedimentation, degradation is also an important process that leads to the elimination of the compounds in wastewater and in the aquatic environment. TCS for instance is degradable under aerobic conditions but also for biodegradation a half-life of 5. Environmental and health profile
and nano-Ag by definition cannot be considered as biodegradable, however, all Ag forms are subject to transformation processes that possibly lead to their removal from the aquatic environment. It has been shown that nano-Ag is immobilized by formation of stable sulfide complexes (Kaegi et al., 2011). Silver sulfide is very insoluble and is much less toxic and bioavailable than dissolved Ag or nano-Ag (Levard et al., 2012). The formation of silver sulfide would thus significantly reduce the risk of silver-based compounds in the aquatic environment. In contrast the formation of degradation products is of concern in the case of TCS, which can form degradation products such as methyltriclosan that is potentially more toxic than the parent compound (Dann and Hontela, 2011). The degradation products of ZnPT are less toxic than the parent compound and are generally of low concern (Madsen et al., 2000). It has also been suggested that antimicrobials might disturb nitrifying bacteria critical to the efficacy of wastewater treatment plants. No effect on nitrifying bacteria was found at lower TCS concentration (Samsøe-Petersen et al., 2003). For Ag, the literature shows contradictory results. Choi and Hu (2009) found an inhibition of the nitrification process from nano-Ag in an idealized simulated waste matrix, while Burkhardt et al. (2010) found no effect of nano-Ag on nitrification in real-world wastewater. Similarly Kaegi et al. (2011) showed that Ag has no significant impact on the function of wastewater treatment processes from laboratory, pilot-scale and municipal-scale waste treatment systems. The octanol–water partition coefficients (Kow) can be a measure of the extent to which a specific compound is taken up by organisms and is often a suitable parameter to compare different antimicrobial substances, particularly for organic compounds. TCS has the highest bioaccumulation potential with a Kow of 4.8 (Dann and Hontela, 2011) followed by Si-QAC with a Kow of 2.9 (NICNAS, 2007). ZnPT in contrast has a much lower bioaccumulation potential with a Kow of 0.9 (NRAAVC, 2001) and the Kow of AgCl and Ag+ are 0.09 and 0.03 (Reinfelder and Chang, 1999). Since substances with a Kow>3 are considered as substances that bioaccumulate because they are more likely to partition into lipids than to stay in the aqueous environment (Thomas and Brooks, 2010), TCS and Si-QAC are more problematic according to this measure. Despite its low Kow there is also some concern about the bioaccumulation potential of ZnPT (Marcheselli et al., 2010).

Comparison of environmental concentrations in the aquatic environment is important to assess if different antimicrobials present a toxicity risk to aquatic life and is typically performed in risk assessment of individual substances. The measured (MEC) and predicted environmental concentrations (PEC) for each antimicrobial compound are shown in Fig. 4. The long historical use of Ag and also more recent use of TCS have led to measurable background concentrations in the aqueous environment, for Ag between 0.03 and 1000 ng/L and for TCS 0.001 and 40,000 ng/L (Dann and Hontela, 2011; Luoma, 2008; NICNAS, 2009; SCCS, 2010; USEPA, 2010, 2011). Whereas the signal of the synthetic TCS is solely the result of relatively recent human use, the environmental Ag concentration is composed of a natural background level from soil and mineral sources together with Ag derived from human use over a period of centuries (e.g. cutlery, currency). Published data for MEC of nano-Ag and Si-QAC was unavailable and for ZnPT only concentrations below the detection limit have been reported (<20 ng/L) (Thomas, 1999).

The PEC for all antimicrobials also stretches across a large range. For nano-Ag, Si-QAC and ZnPT only modeled concentrations are available. The predicted no effect concentrations (PNEC), which indicate the concentration up to which no adverse effect on the most sensitive organisms can be expected, are in the range of the PEC and MEC values for all compounds except for Ag. For Ag the PNEC is below the PEC but still in the range of the MEC, however, this analysis makes no distinction between biologically active dissolved silver and silver transformed into sulfides. This implies that the expectation for risk to aquatic life based on a risk quotient (PEC/PNEC) >1 depends strongly on the locally measured concentration and chemical composition of the compound. Other studies concluded for nano-Ag that there is no expected risk with risk quotients <1 (Gottschalk et al., 2009; Mueller and Nowack, 2008; USEPA, 2011). Blaser et al. (2008) listed PEC and PNEC values and did not indicate a risk expectation from Ag use. A risk assessment for Si-QAC found no expected risk for most of the examined scenarios (NICNAS, 2007). For ZnPT one study found no expected risk (Turley et al., 2000) and in another study ZnPT turned out to be problematic in harbors and unproblematic in the open ocean (Madsen et al., 2000). For TCS one report expects a risk for aquatic organisms (NICNAS, 2009), two reports found a risk quotient >1 but did not generalize their finding (Remberger et al., 2005; Samsøe-Petersen et al., 2003) and another risk assessment by von der Ohe et al. (2011) suggested the monitoring of triclosan as priority substance.

5.2. Human health

Exposure pathways and potential health effects need to be considered in order to evaluate the safety of antimicrobial compounds for humans. The type of active material (free or bound), the concentration in the product, the routes of exposure and the frequency of use all influence the extent to which humans may be exposed to antimicrobials in a textile product (Wijnhoven et al., 2009). Potential exposure routes are comparable for Ag, nano-Ag, TCS, Si-QAC and ZnPT as they may all be used for skin-contact uses and so people can potentially be exposed to the compounds through dermal, oral or inhalation pathways. Among the parameters that are usually assessed to determine the risk profile of an antimicrobial are toxicity (acute and chronic), skin sensitization and irritation, disturbance of skin ecology as well as genotoxicity, mutagenicity, carcinogenicity and teratogenicity (Kramer et al., 2006). Antimicrobials are designed to specifically address microorganisms but most of them have a relatively low acute toxicity to humans with oral LD50 (lethal dose at which 50% of the test animals die) measured in rats between 92 mg/kg for ZnPT (SCCNP, 2002) and >5000 mg/kg for Ag (USEPA, 1992) and Si-QAC (USEPA, 2007). Skin sensitization and (sub)chronic toxicity are highly relevant parameters for textile antimicrobials and may be used to compare the hazardous effects of various substances. There are no concerns for skin sensitization for bulk Ag (USEPA, 1992) and nano-Ag (Christensen et al., 2010) and there is only limited concern for dermal sensitization for ZnPT (USEPA, 2008a), however there is evidence of skin sensitization for Si-QAC (NICNAS, 2007) and for TCS (Hahn et al., 2010). Chronic toxicity studies aim to identify suitable NOAEL (no observed adverse effect level) or NOEL (no observed

Fig. 4. Measured environmental concentrations (MEC), predicted environmental concentrations (PEC) and predicted no effect concentration (PNEC) for the aquatic environment (note the log scale). Data was extracted from the following papers and reviews: nano-Ag predicted (Gottschalk et al., 2009); Ag measured (Luoma, 2008; USEPA, 2010, 2011); Ag predicted (Blaser et al., 2008); TCS measured (Dann and Hontela, 2011; NICNAS, 2009, SCCS, 2010); TCS predicted (NICNAS, 2009; Samsøe-Petersen et al., 2003); Si-QAC predicted (NICNAS, 2007); ZnPT measured (Thomas, 1999); ZnPT predicted (Madsen et al., 2000; Turley et al., 2000). n.a.: no data available; bdl: below detection limit.
effect level) to determine the chronic harmful doses of a substance. The studies reviewed here indicate that ZnPT has an oral NOAEL in rats of 0.5 mg/kg/day (SCCNFP, 2002) compared to oral NOAEL in rats of 40 mg/kg/day for TCS (NICNAS, 2009), 30 mg/kg/day for nano-Ag (USEPA, 2011), 240 mg/kg/day for Si-QAC (USEPA, 2007) and an oral NOEL in rats of 63.5 mg/kg/day for bulk Ag (USEPA, 1992). For all antimicrobial compounds discussed in this review there remain open questions regarding toxicity and effects on human health that can benefit from further research. Ag for instance is seen as relatively non-toxic to humans and nano-Ag continues to be a topic of intense research (Christensen et al., 2010). For nano-Ag it should be noted that historical data and real-life experience with nanoparticulate Ag (such as colloidal silver) strongly suggests that the toxicity of nano-Ag is not significantly different to bulk or dissolved Ag (Nowack et al., 2011). This was also confirmed in a recent study that allocated the antimicrobial effect of nanosilver entirely to the release of silver ions and reported the absence of particle-specific effects (Xiu et al., 2012). The effects and toxicity of TCS are of concern as TCS is suspected to act as an endocrine disruptor (Dann and Hontela, 2011) and has been observed to be distributed in human tissues (Adolfsson-Erici et al., 2002). Dann and Hontela (2011) consider the use of TCS as safe but emphasize that further research is required to exclude adverse effects. Although Si-QAC is a corrosive chemical, the USEPA does not expect any severe effects of Si-QAC use on human health (USEPA, 2007) and ZnPT may present corrosive chemical, the USEPA does not expect any severe effects of Si-QAC use on human health (USEPA, 2007) and ZnPT may present some risks due to potential for development and neurotoxicity (USEPA, 2008a).

5.3. Development of resistance

For any substance that addresses microorganisms there is a need to consider the potential for development of resistance. The propensity to induce resistance depends on the chemical nature of the substance, on the properties of the microorganisms and on environmental conditions (Maillard, 2005). An important factor for risk of resistance development is if the antimicrobial substance has a single mode of action against the target microorganism and particularly if it shares a mode of action with antibiotics used in clinical environments (Kuck and Kugler, 2001). In contrast, antimicrobials with multiple modes of action are generally associated with lower risk of resistance development. The impact of these factors on the risk to develop widespread resistance under environmentally relevant conditions needs to be carefully evaluated.

As for many antimicrobial substances, TCS, QAC, Ag and ZnPT have exhibited development of resistance in some microorganisms under idealized laboratory conditions (Guardiola et al., 2012; Malek et al., 2009; SCCS, 2010; SCENIHR, 2009). For a discussion of the underlying processes related to the potential for acquisition of resistance we refer to the literature, e.g. (Dann and Hontela, 2011; Silver, 2003). TCS has been thoroughly investigated with respect to potential for resistance in the laboratory, nevertheless the Scientific Committee on Consumer Safety (SCCS, 2010) highlights that despite the fact that the TCS levels in the environment might theoretically lead to the development of resistance, there is a lack of evidence if the compound induces resistance in real-life. Similarly for Ag an extensive survey of wild bacteria strains showed no evidence of resistance to Ag (Jakobsen et al., 2011). Percival et al. (2005) emphasized that despite the long history of human use, and exposure to natural sub-inhibitory levels of silver, no widespread occurrence of resistance has been observed. Due to a lack of data on the resistance potential under environmentally relevant conditions of the antimicrobials discussed in this review and also due to the inherent difficulty of exhaustively surveying all bacteria strains and use contexts, it is not possible to reach a definitive conclusion in respect to which antimicrobial is more or less prone to select for resistance (SCENIHR, 2009). While further research on this topic is needed to understand fundamental microbiological mechanisms, there seems to be a large gap between idealized laboratory studies and a considered reflection upon any realistic potential for risk of resistance development under environmentally relevant conditions. It should be noted that antimicrobial use in textiles is demonstrably a relatively minor use pattern for antimicrobials and any analysis of risk of resistance should be seen in context of other more prevalent, wide-spread and long-use application sectors of the substances. Meanwhile the selection of antimicrobials with multiple modes of action and high durability on the treated textile should be preferred.

6. Use of antimicrobials from a life cycle perspective

When selecting antimicrobial treatments for textiles, the advantages of a given antimicrobial substance should outweigh the potential environmental costs of the antimicrobial application (Blackburn, 2004). Potential environmental benefits of antimicrobial treated textiles include a prolonged useful period of textile wear, potential for less frequent laundry cycles, lower washing temperatures and a reduction of chemical consumption in each wash cycle. More efficient substances that require lower dosing levels while achieving durable functionality are desirable (Bauer et al., 2008). Environmental impact of an antimicrobial substance can derive from raw material selection, antimicrobial production, textile treatment processes and subsequent use and disposal of the product. The first published study to address the environmental costs of different antimicrobial textile products involved a life cycle assessment of a conventional T-shirt compared to T-shirts treated either with TCS or nano-Ag (Walser et al., 2011). The authors showed that the contribution of the use of TCS to the greenhouse gas emissions of a T-shirt was insignificant and Blackburn (2004) stated that the additional resources consumed to apply an antimicrobial treatment are negligible compared to the environmental benefits. Walser et al. (2011) also demonstrated that the environmental costs of nano-Ag functionalized T-shirts were highly dependent upon the nano-Ag production technology. Nevertheless multiple studies agree that the use phase (laundry, drying and ironing) strongly influences the environmental performance of textiles (Cartwright et al., 2011; Meyer et al., 2011; Walser et al., 2011). The potential environmental benefits of antimicrobial textiles, enabling a reduction of energy and water demand during use, should therefore be considered in the evaluation of antimicrobial use in textiles. Given that there are billions of people on earth using on average 10 kg of textiles each year (FAO and ICAC, 2011), the potential benefits of antimicrobials textiles to reduce the environmental burden of textiles should be integral to any discussion on the sustainability of textiles. While there is clear potential to realize significant environmental benefits through antimicrobial treatments, further research to examine the potential for uptake of modified textile care practices of consumers would be valuable. Adopting a broader perspective of the role that various antimicrobial technologies can play within the textile sector and evaluating both the environmental costs and benefits of these uses would contribute to informing which antimicrobial technologies provide the highest benefit while minimizing risks to the environment and human health.

7. Conclusions

7.1. Antimicrobial production volumes

Up-to-date market information on the consumption of antimicrobials in textiles is scarce. Uncertainty about actual consumption levels was compounded by different sources referring variously to biocides, antimicrobials or active ingredients. Nevertheless the reviewed data provided a valuable contribution to future estimates about antimicrobial usage. Synthetic organic compounds clearly dominate the antimicrobial volumes used in the textiles market (1300–1400 metric tonnes in
7.2. Regulatory assessment of antimicrobials

Antimicrobial substances are amongst the most thoroughly regulated class of chemicals. Changes in regulations can have a major influence on antimicrobial use patterns and the market share of particular compounds. Altering the antimicrobial use pattern in textiles would result in significantly reduced antimicrobial flow to the environment only if textiles are a major contributor to the total usage volume for a given antimicrobial. Textiles are a higher proportion of total TCS use for instance compared to the use of QAC where textile use is a minor proportion of all QAC uses. It is therefore essential that regulations are made in consideration of the full context of antimicrobial usage patterns. Similarly a disproportional focus on single substances, or inconsistency in the regulatory assessment process applied to different actives, can result in the substitution by less suitable antimicrobial substances with potentially counterproductive outcomes for the environment such as an increased total antimicrobial use. The proportion of total antimicrobial consumption used in textiles seemed to be lowest with Si-QAC and highest with nano-Ag however there is uncertainty about the nano-Ag fraction actually used in textiles because a range of silver products use unspecified Ag forms that are likely based on nanofoms (Nowack et al., 2011). The most favorable application rate (lowest dosing level) was found for nano-Ag, in contrast to bulk silver products (such as silver filaments or silver-coated fibers) that require significantly higher application rates to achieve the desired functionality. The use of less material intensive compounds, such as metallic nano-Ag and nanosilver chloride, therefore has clear potential to significantly decrease the overall environmental burden of antimicrobial exposure. Different antimicrobial technologies can show a range of durabilities on textiles but this could not be conclusively assessed based on published literature. The evaluation of durability consequently considered if the antimicrobials are suitable to be incorporated into synthetic fibers which has potential to enable a more durable antimicrobial treatment relative to topical treatments (Cressler et al., 2010). The durability of ZnPT was classified as being low compared to silver-based compounds. The relative evaluation of the persistence of the compounds in the environment showed that synthetic organic antimicrobials such as TCS can persist in the environment for some time and Ag transforms rapidly into other silver forms. Nevertheless it must be considered that Ag cannot be degraded or removed from the environment as it is a mineral substance. For all antimicrobials except for ZnPT the data indicated that they can be easily removed in wastewater treatment plants which ultimately results in a low release to the environment.

7.3. Overall evaluation of antimicrobials

An overall comparison of the antimicrobial substances according to selected criteria presented in this review is shown in Table 6. The table summarizes three main areas of analysis: 1) technical criteria such as consumption volume in textiles, application rates and durability; 2) environmental criteria such as persistence in the environment, elimination in wastewater treatment plants, bioaccumulation and environmental concentrations and 3) criteria related to human health such as sensitization and chronic toxicity. The evaluation differentiated between different Ag forms. Data relevant to metallic Ag particles or Ag salts in the nano-range was included in the category “nano-Ag” and data that referred to Ag in general, including ion exchange or bulk Ag (e.g. silver wires) was included in the category “Ag bulk”.

The proportion of the total antimicrobial consumption used in textiles showed that synthetic silver compounds were used in a significantly lower amount compared to silver-based antimicrobials. Differences in antimicrobial concentrations in the environment were evaluated on the basis of the measured or predicted environmental concentrations and the chronic toxicity at low concentrations. The Chronic toxicity at low concentrations was classified as low. The Relative Ranking was based on the cumulative number of dots (fewer dots equals lower impact/exposure).

Table 6

Comparative evaluation of the antimicrobials according to technical, environmental and human health criteria based on reviewed literature. The black dots indicate to which extent the use of a particular antimicrobial can result in increased exposure (technical criteria) or to which extent the behavior and effects of a compound are of concern (environmental and human health criteria); i.e. one black dot indicates low anticipated exposure/impact, more black dots indicates higher anticipated exposure/impact and dots in square brackets illustrate uncertainty.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Nano-Ag a</th>
<th>Ag bulk b</th>
<th>TCS</th>
<th>Si-QAC</th>
<th>ZnPT</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A small (●) or a large fraction (●●●) of the total compound consumption as antimicrobial is used in textiles.</td>
</tr>
<tr>
<td>1 Proposition of overall use in textiles</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>The most favorable application rate (lowest dosing level) was found for nano-Ag, in contrast to bulk silver products (such as silver filaments or silver-coated fibers) which require significantly higher application rates to achieve the desired functionality.</td>
</tr>
<tr>
<td>2 Application rate</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>Fast degradation/transformation (●) or limited degradation (●●●) under environmental conditions.</td>
</tr>
<tr>
<td>3 Durable functionality</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>Efficient removal in the wastewater treatment process (●) that results in low exposure of the environment.</td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low (●) to high (●●●●●) potential for bioaccumulation based on octanol-water partition coefficients.</td>
</tr>
<tr>
<td>4 Persistence in the environment</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>The measured or predicted environmental concentrations are lower (●) or higher (●●●●●) than predicted environmental no effect concentrations.</td>
</tr>
<tr>
<td>5 Removal during wastewater treatment</td>
<td></td>
<td></td>
<td>●●</td>
<td>●</td>
<td></td>
<td>Eficient removal in the wastewater treatment process (●) that results in low exposure of the environment.</td>
</tr>
<tr>
<td>6 Potential for bioaccumulation</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>Low (●) to high (●●●●●) potential for bioaccumulation based on octanol-water partition coefficients.</td>
</tr>
<tr>
<td>7 Environmental concentrations</td>
<td></td>
<td></td>
<td>●●</td>
<td>●●●●●</td>
<td>●●●</td>
<td>The measured or predicted environmental concentrations are lower (●) or higher (●●●●●) than predicted environmental no effect concentrations.</td>
</tr>
<tr>
<td>Human health</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low (●) to medium (●●●) dermal sensitization potential based on experimental studies from literature.</td>
</tr>
<tr>
<td>8 Dermal sensitization potential</td>
<td></td>
<td></td>
<td>●●</td>
<td>●</td>
<td></td>
<td>Chronic toxicity unlikely (●) or likely (●●●) at low concentrations based on literature values about No Observed (Adverse) Effect Levels.</td>
</tr>
<tr>
<td>9 Chronic toxicity at low concentrations</td>
<td></td>
<td></td>
<td>●●</td>
<td>●</td>
<td></td>
<td>Chronic toxicity unlikely (●) or likely (●●●) at low concentrations based on literature values about No Observed (Adverse) Effect Levels.</td>
</tr>
<tr>
<td>Relative Ranking</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

n.a.: no data available.

a Nano-Ag: includes metallic or salt particles in the nanoform.
b Ag bulk: includes metallic silver threads, silver coated yarns, ion-based additives and considers sources that refer to Ag in general.
c Silver as an element is not degradable, however, it rapidly transforms to environmentally benign silver forms (e.g. silver sulfide) under environmental conditions.
d Ranking from 1 (lowest impact) to 5 (highest impact) based on the cumulative number of dots (fewer dots equals lower impact/exposure).
environment. The high bioaccumulation potential for TCS is of particular concern and high environmental concentrations were in particular reported for bulk silver however this should be seen in the context of silver being a material present naturally in the mineral environment and of the long historical use of silver by humans. In the case of dermal sensitization in particular TCS and Si-QAC might be of concern. ZnPT appears to be the substance with the highest relative toxicity potential. Due to the lack of published literature, no differentiation could be made between the potential to develop resistance of different antimicrobials and consequently this topic was not included in the evaluation.

The results of this comparative evaluation indicate that in particular the use of TCS and the use of bulk silver forms (e.g. silver metal threads and silver coated yarns) requiring high application rates are least preferable. Nanoscale silver and silver salts that achieve functionality with very low application rates offer clear potential benefits for textile use. The results of this evaluation should be seen as a starting point to more distinctive scientific assessments of antimicrobials in textiles. The extent of published data varied for the compounds, complicating the comparison between substances. Experiments about the durability of different antimicrobials under controlled conditions are necessary to definitively examine which antimicrobial treatments offer the highest durability, which is an important parameter for the sustainability of the compounds. Data on the environmental behavior and environmental concentrations of the compounds in different environmental compartments and the extent to which antimicrobial use in textiles contributes to the environmental concentrations compared to other application sectors will further improve their comparative evaluation. In addition the comparative evaluation of antimicrobials must consider that all of these treatments can play a role in reducing the frequency and/or intensity of textile care, which in turn can give potential for significant savings in water, energy and chemical consumption. The benefits of particular antimicrobial substances should be weighted along with the risks of the compounds to inform practical choices of best available technologies for textiles and also for policy makers to avoid counterproductive consequences of compound-specific regulatory decisions on the environment and consumers. Antimicrobial substances are available today that provide this balance and they should also be the focus of future product development.

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