12
Environmental Considerations of and Societal Reactions to Nanotechnology in the Food Sector

Michael Siegrist, Bernd Nowack, and Hans Kastenholz

12.1
Introduction

Food products and food packaging containing engineered nanoparticles are already commercially available [1]. Industry and governments invest considerable amounts of money in employing this technology for new applications in such areas as food packaging, food processing, food safety, and agricultural production [2]. It is therefore expected that nanotechnology will be even more important in the near future [3].

Nanotechnology has great potential to generate new products in various domains. Because nanotechnology may affect so many aspects of human life, risk assessment errors may result in irreversible damage [4]. Although many studies examining possible applications of nanotechnology or nanoparticles have emphasized that the new technology may have adverse effects on health and environment, no conclusions could be reached due to lack of data. The life cycle assessment of nanotechnology applications is currently in its very infancy [5]. It is difficult, therefore, to assess the environmental and human health impacts of nano-based products and services. Overall, we currently know much more about the possible benefits of this technology than about the possible risks. This makes regulation very difficult, since there are few hard facts on which such regulations could be built [6–7].

Nanotechnology allows the creation of materials with new, desired properties. The very same properties that lead to potentially great benefits may also result in unwanted risks, however [8]. The novel properties of nanomaterials and the potentially broad introduction of nanomaterial-based products have raised many concerns over their consequences for human and environmental health [9]. Results of risk assessment studies suggest that some nanomaterials may have damage potential if they are exposed to humans or the environment [10]. It has been concluded that there is a lack of knowledge regarding the toxic effects of free nanoparticles, and that not enough is known about dosage and exposure for traditional risk analysis models [4]. The situation is similar to that for other new technologies.

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Lack of data and understanding make it very difficult to reliably assess the potential and the risks of nanotechnology.

There are various pathways through which humans may be confronted with nanoparticles in foods. Figure 12.1 shows the ways humans could theoretically be exposed to food containing nanomaterials:

- consumption of foods or health supplements for which nanoparticles were used in the manufacturing process;
- consumption of nanoparticles that have migrated into foods from food packaging coated with nanomaterials;
- consumption of foods exposed to nanomaterials during farming practice.

In addition, there are indirect pathways by which nanoparticles can end up in food:

- nanoparticles in discarded packaging eventually get into the environment – ingested nanoparticles can be excreted again, removed from wastewater, and added to soil by sludge, or nanoparticles are not removed during wastewater treatment;
- nanoparticles can also enter the environment from non-food products and applications, either through wastewater, solid waste or direct input;
- once in the environment, nanoparticles can be taken up by foods and thus return back into the food cycle.

12.2 Life Cycle of Nanotechnology Food Products

The release of nanoparticles can occur throughout the whole life cycle of products [11], and it is thus important to take into account the possible exposures to

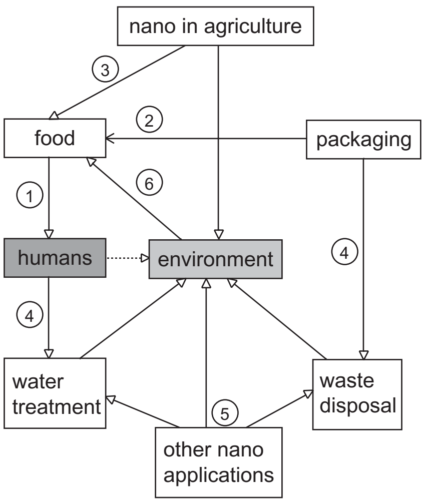

Figure 12.1 Nanoparticle flows between food, humans, and the environment.

nanoparticles in different phases of the life cycle of a product [12]. Critical points are during (i) production and shipping, where release into the air is most likely, (ii) production of the final product, (iii) use, and finally (iv) disposal or recycling. The amount of nanoparticles released by the different processes depends on several factors: the nanoparticle stock in the product, the product's lifetime, the way nanoparticles are incorporated into the material, and the actual use/usage of the product [11]. Products with a long lifetime, a loose incorporation of the nanoparticle and/or an intense use (e.g., through frequent cleaning) will most likely not contain any nanoparticles at the time of disposal. On the other hand, factors such as short lifetime, low usage, and strong fixation of nanoparticles increase the likelihood that particles will not be released until disposal. In the following subsection, a few examples from the food, food packaging, and agriculture sectors are presented. Benefits and possible risks for humans and for the environment are discussed.

12.2.1 Food

Acids present in soft drinks may have erosion effects on teeth. Through the use of nanotechnology, new functional soft drinks may be created, which have less erosion effects on teeth than conventional soft drinks [13]. Encapsulation and delivery systems are another example of the use of nanotechnology as a tool for new products in the food industry [14]. Vitamins or other supplements are packed in nanoparticles and infused into the foodstuffs. Encapsulation increases stability, and it allows for controlled release of the ingredients to specific places in the human body. Personalized beverages and foods could also be of some interest to consumers and producers [1]. After purchase of the food product, it is customized according to the preferences of the consumer. Ultrasonic frequency, heat or other triggers are used to release varying flavors, colors or nutrients from nano-emulsions in drinks or food products.

In all these applications, the life cycle of the products is clear because they are intended for complete human consumption. The entry point of the nanoparticle into the body or the environment after passage through the gut is therefore well defined and easily quantifiable.

12.2.2 Packaging

Nanotechnology promises new food packaging with great benefits. Nowadays, most packaging materials are produced from fossil fuels, and disposal therefore is often problematic. Nanocomposites may be used to create edible and biodegradable films that help to reduce packaging waste [15]. Antimicrobials and antioxidants incorporated in films should increase the shelf-life and quality of coated food [14]. In the future, nanosensors embedded in the packaging will inform the consumer as to whether the food is still good or already bad [15].

In these applications, release of nanoparticles can occur during the storage phase, and transfer to the food is possible. The nanoparticles that stay within the packing are then disposed of or recycled (e.g., with compostable plastics).

12.2.3 Agriculture

Almost no applications of nanomaterials in agriculture are on the market yet, but a lot of research activity is in progress. In Switzerland, for example, only one plant protection product containing nanoparticles was found [16], a nano-silver-containing spray for indoor and outdoor use on plant leaves, with low sales volume [17]. There is some evidence that research is ongoing for new formulations of plant protection products with quantitatively high application potential. Without mentioning specific products, a Nanoforum Report states that many companies have products with nanoparticulate ingredients within a size range of 100–250 nm and that other companies suspend herbicidal or pesticidal nanoparticles of 200–400 nm size in oil or water [18]. The current research focus is on encapsulation, use of organo-clays, and improved storage.

Nanotechnology in fertilizers can be used in this field for slow-release mechanisms such as entrapping, encapsulating or dispersing the active agents in a matrix of biodegradable or inert material. To date, no indications of real applications have been found in the scientific literature, on the Web, and in feedback from experts or associations [16]. The main research focus for the application of nanoparticles in fertilizers is placed on slow and controlled release of fertilizers. In that group, various polymers and clays are mentioned repeatedly. For clays, the benefit of nanoparticulate size is not clear, as in most cases the interlayer distance matters, and in fact several patents were found using clay particles or platelets of larger size. Plants take up nutrients mainly by roots or via leaves, and slow and controlled release is advantageous for nutrient supply on both routes. Foliar fertilizers are often used to satisfy short-term nutrient supply, where a nanoparticulate nutrient may be better for efficient nutrient uptake.

12.2.4 Non-Food Sector

All nanoparticles that are used in any imaginable application may end up in the environment at some stage of their life cycle, and thus may be fed back into the food cycle. However, current information on the release of nanoparticles from products into the environment is scarce. The release of nano-titanium dioxide (TiO_2) from coatings on wood, polymer, and tile were the highest from coated tile, and ultraviolet light increased the release of particles [19].

Release of nanoparticles into the environment can also occur at the end of the life of nano-products, when they are dumped into landfills or burned in waste incineration plants. Although the particle filters of water incineration plants are very effective, low concentrations of nanoparticles can leave the stack and be distributed by air. However, the largest input of nanoparticles into the environment is most likely by products that are used up during use, for example, sunscreens. All nanoparticles contained in sunscreen will be present in water, either directly washed off the skin into open waters or removed during showering. This pathway is very important not only for nano-TiO_2 but also for nano-silver [20].

There are socks on the market with nano-silver as an antimicrobial agent. During the washing process, some of these nano-silver particles may end up in the sewage water. A model by Benn and Westerhoff [21] suggests that a typical wastewater treatment facility could treat a high concentration of silver stemming from socks or other textiles. The authors concluded, however, that increased consumption of textiles with nano-silver may restrict the use of bio-solids as a fertilizer for agricultural lands. However, silver is also released in ionic form from nanoparticles, and this was considered to be the major process of silver release from plastics and textiles [22]. Silver from nanoparticles was found to contribute only 0.5–15% to the total silver flow into the environment.

12.3 Occurrence of Engineered Nanoparticles in the Environment

There is a lack of information not only about the economic impact of nanotechnology, but also about the type and quantity of industrially used, manufactured nanoparticles [23]. As a result, it is nearly impossible to quantify the level of exposure for consumers and the environment. Results of an initial survey in Swiss industry suggests that the largest quantities of nanoparticles are used in the production of cosmetics, food, paints, and powders [24]. More information is needed about the number of people exposed to engineered nanoparticles and what amount of material these people are exposed to. It is clear that, with an increased use of engineered nanoparticles, the potential for unintended environmental consequences will also increase [25].

Because analytical measurements of engineered nanoparticles in the environment are lacking, the expected concentrations have to be modeled with the help of extrapolations and analogies. A recent study modeled the silver emissions from nano-silver containing biocidal products and compared the expected concentrations in the environment with a reference emission [22]. In this study, nano-silver served only as a silver ion (Ag^+) source, and no particulate silver emissions were considered; therefore, no concentrations of nano-silver in the environment were modeled.

Another study used a life cycle perspective to model the quantities of engineered nanoparticles released into the environment [20]. Three types of nanoparticle were studied: nano-silver (nano-Ag), nano-TiO_2 and carbon nanotubes. The quantification was based on a substance flow analysis from products to air, soil, and water in Switzerland. The following parameters were used as model inputs: estimated worldwide production volume, allocation of the production volume to product categories, particle release from products, and flow coefficients within the environmental compartments. To estimate a possible risk, the predicted environmental concentrations were then compared to the predicted no-effect concentrations derived from the literature.

The expected concentrations of the three nanoparticles in the different environmental compartments vary widely, caused by the different life cycles of the nanoparticle-containing products. The predicted environmental concentration values for nano-TiO_2 in water are 0.7–16 μg l^{-1}. The results of this study make it possible for the first time to carry out a quantitative risk assessment of nanoparticles in the environment and suggest further detailed studies of nano-TiO_2. The modeling suggests that currently nano-silver poses little or no risk to soil organisms. The risk quotient (predicted no-effect concentrations divided by predicted environmental concentrations) for water is less than one-thousandth. Also, in the high-exposure scenario, the modeling suggests that currently little or no risk is to be expected from nano-Ag in the soil compartment and the water in general. The modeling suggests that nano-TiO_2 may pose a risk to aquatic organisms, with a risk quotient between about 0.73 and 16 or more. By contrast, the risk quotient for air is smaller than 0.001.

A similar study has been done for the UK [26], although with a different approach. Based on assumed market penetrations of nano-products and the known usage of these products, concentrations in water, air, and soil were modeled. For the 10% market penetration model, which probably overestimates current exposure levels, concentrations of silver, aluminum, and fullerene concentrations were predicted to be in the range of nanograms per liter, whereas nano-TiO_2, zinc oxide, and hydroxyapatite are predicted to be in the micrograms per liter range.

12.3.1
Environmental Behavior of Nanoparticles

The main processes that are acting on nanoparticles in the environment and that are determining their environmental fate are aggregation–disaggregation and adsorption–desorption [27]. Nanoparticles interact among themselves and with other natural nanoparticles or larger particles. The formation of aggregates in natural systems can be understood by considering physical processes, that is, Brownian diffusion, fluid motion, and gravity. Aggregation is dependent on particle size and results in efficient removal of small particles in environmental systems [28]. To quantify the stability of nanoparticles in the environment, we have to predict the stability of their suspension and their tendency to aggregate or interact with other particles [29]. The nature of the nanoparticle is modified by adsorption processes [30], and especially the surface charge plays a dominant role [31, 32].

The movement of nanoparticle in porous media is impeded by two processes: straining or physical filtration, where the particle is larger than the pore and is trapped; and true filtration, where the particle is removed from solution by interception, diffusion, and sedimentation. However, particles removed from solution by such processes can readily become resuspended upon changes in the chemical or physical conditions (e.g., changes in pH, ionic strength, and flow rate [33, 34].

Several studies have investigated the transport of a wide range of engineered nanoparticles through porous media [35–37]. Particles smaller than 100 nm are predicted to have very high efficiencies of transport to collector surfaces due to Brownian diffusion. If all particle–collector contacts were to result in particle attachment to the collector, these small particles would be retained to a large extent by the porous medium. However, nano-sized silica particles were not appreciably removed, and also anatase nanoparticles were only removed between 55% and 70%, depending on the flow velocity [37]. The most efficient removal was observed for an iron oxide nanoparticle [36]. These studies show that the collector efficiency for nanoparticles can be very different and that especially the surface-modified nanoparticles displayed high mobilities. Also the environmental conditions are important, most important being the pH.

Owing to their high surface area, nanoparticles have a high sorption capacity not only for metal ions and anions [38, 39] but also for organic compounds [40–42]. Contaminant sequestration is accomplished mainly by surface complexation, but aggregation of particles may encapsulate sorbed surface species. This strong interaction of metal ions and oxide nanoparticles is very important for the behavior and cycling of metals in the environment [43]. The interaction of nanoparticles with toxic compounds can both amplify as well as alleviate the toxicity of the compounds. Nanoparticles can have an advantageous influence on toxicants in the environment by reducing the free toxicant concentration by adsorption onto their surfaces and hence reducing the toxicity of the pollutant.

12.3.2 Toxicology of Nanoparticles

The most important routes for nanoparticles entering the human body are through the gastrointestinal tract, the skin or the lungs [44]. It is obvious that, for food products, the most likely route is through the gastrointestinal tract. The distribution of the nanoparticles in the body is strongly determined by the nanoparticle's surface characteristics [45]. Engineered nanoparticles differ in respect to material, size, surface, and shape. It is not possible, therefore, to make general claims about the health risks of nanoparticles. As a consequence, it has been suggested that engineered nanoparticles need to be assessed on a case-by-case basis [46].

Concern has been raised over the safety of nanoparticles because they have properties that are clearly associated with pathogenicity in particles [47]. Several recent papers have highlighted this area of toxicology, the gaps in research, and possible testing strategies for nanoparticles [10, 12, 48]. The consistent body of evidence shows that nano-sized particles are taken up by a wide variety of mammalian cell types, and are able to cross the cell membrane and become internalized [49–51]. The uptake of nanoparticles is size dependent [52, 53]. In general, cells can survive low concentrations of nanoparticles ($<10\,\mathrm{mg\,l^{-1}}$); however, at high doses, cytotoxic effects emerge in a dose- and time-dependent manner for many nanoparticles [48]. While the causes of the increase in cell death observed at higher concentrations and longer exposure times are material specific, the generation of reactive oxygen species is a common finding. The small particle size, a large surface area, and the ability to generate reactive oxygen species play major roles in the toxicity of nanoparticles [9]. Inflammation and fibrosis are effects observed on an organism level, whereas oxidative stress, antioxidant activity, and cytotoxicity are effects observed on a cellular level [10].

The potential effects of nanoparticles in the gastrointestinal tract are largely unknown [54]. A healthy digestive system only allows absorption of nutrients from the gut after digestion of foods. The gut wall is designed to ensure the passage of nutrients and to prevent the passage of larger or foreign material. Transport of particles across the epithelium can occur by the paracellular route (between cells) and the transcellular route [55]. The paracellular route is limited because of the very small surface area of the intercellular space and the tightness of the junctions between cells (pore diameter just 0.3–1 nm). Transcellular uptake of nanoparticles occurs by transcytosis, a process by which nanoparticles are taken up by cells. This transport depends on several factors [55]: (i) the physicochemical properties of the particles, (ii) the physiology of the gastrointestinal tract, and (iii) the animal model used to study the uptake. In general, the nanoparticle uptake increases as the particle diameter decreases.

12.4
How Should Society Deal with Uncertainty?

The use of nanotechnology may result in applications with numerous benefits. However, as outlined above, the very same properties that make nanotechnology or engineered nanoparticles so promising are also the properties that could be responsible for unwanted effects in humans and in the environment. Owing to the lack of available data related to toxicity, exposure, and life cycle of nanotechnology applications, regulatory decisions are in a state of ambiguity or high level of uncertainty. Too much regulation may result in forgoing the benefits of nanotechnology, and too relaxed regulation may result in damages [56]. Some have expressed fear that governmental agencies may not regulate engineered nanoparticles quickly enough, and that therefore the development and implementation of voluntary standards of care are important [57]. Others have called for a moratorium on the use of nanomaterials, especially on the further commercial release of food products, food packaging, food contact materials, and agrochemicals, until nanotechnology-specific safety laws are established and the public is involved in decision-making.

Studies have shown that perceptions on regulatory policy issues in the field of nanoparticulate materials differ among the involved stakeholders [46]. Industry, scientists, governmental bodies, and environmental advocacy groups find regulatory interventions useful, but they are of different opinions as to whether regulations should be evidence-oriented or precaution-oriented, voluntary or top-down controlled. Whereas regulatory bodies and industry do not see the need to regulate this area until more scientific evidence indicates that nanomaterials may be harmful, non-governmental organizations are asking for more proactive risk management strategies. However, companies are legally obliged to guarantee that their products are safe and that they do not cause any harm to human health and the environment.

In recent years, different integrative risk management frameworks for nanomaterials have been developed to overcome the apparent weaknesses of previous approaches [58–60]. Each of the frameworks shares common elements, including integration of hazard assessment, exposure assessment, risk management, and risk communication. However, it should be noted that the risk and safety research and management approaches of nanoparticulate materials are still mainly focusing on non-food nanomaterials and aspects. Appropriate risk governance strategies for nanoscaled materials in food products and food packaging are still in their infancy [7].

12.4.1
Public Perception of Nanotechnology

Several surveys have examined public perception of nanotechnology. Even results of recent studies suggest that public awareness of nanotechnology is low, and that knowledge about nanotechnology is limited at best [61–63]. These studies examined attitudes toward nanotechnology in the abstract, as opposed to attitudes toward realistic products. Based on these studies, it is difficult to predict how the public will react toward real products. It seems likely that perceived benefits largely determine willingness to buy nanotechnology applications.

Owing to the fact that most people do not have much knowledge about nanotechnology, and that they do not have clear ideas about the promises of this technology, study participants should be given some information about nanotechnology, and the applications should be briefly described to enable participants to create attitudes toward nanotechnology applications. Results of a Swiss study examining a broad set of nanotechnology applications, ranging from water sterilization to ammunition, suggest that lay people perceive the various nanotechnology applications differently [64]. More specifically, results showed that lay people perceived applications such as food packaging or water sterilization as more dreaded risks than applications that are not related to food products. On the surface, there seem to be some parallels to gene technology. Consumers are less likely to accept genetically modified (GM) food products compared with medical applications [65]. The research in the domain of nanotechnology further emphasizes that the public is especially concerned when new food technologies are introduced.

In two studies, we examined lay people's perceptions of different nanotechnology foods and nanotechnology food packaging applications [66–67]. Results suggest that lay people perceive nanotechnology packaging as being more beneficial and less risky than nanotechnology foods. Thus, consumers may be less likely to accept nanotechnology foods than innovations related to packaging.

In the study by Siegrist *et al.* [67], 19 different applications were examined. Lay people perceived individually modifiable foods as the most risky applications. Customization of the product, in which nanoparticles release varying flavors, colors or nutrients when warmed in the microwave, depending on the wavelength chosen, was not an accepted innovation for most participants. The second highest risk ratings were received by health-promoting feed and forage. In such an application, livestock feed and forage is infused with proteins encapsulated in nanoparticles. Based on lay people's risk ratings, nanoparticles used for removing toxins in the soil had the seventh highest risk rating of the 19 applications. Overall, results suggest that lay people based their risk assessments, not on the possible environmental impact of the applications, but rather on whether or not the nanoparticles are consumed. Participants may not have taken into consideration the possible migration of nanoparticles from the food packaging to the food. As a result, additional and new information may have changed lay people's perception of nanotechnology food and food packaging applications.

In several countries, public participation and focus group studies have been conducted, in which participants received information about nanotechnology in order to form attitudes toward this new technology [68, 69]. In Switzerland, focus groups were organized to facilitate public discussion and to help decision-makers in assessing nanotechnology [68]. Participants read a brochure about nanotechnology prior to the meetings, and they therefore had some basic knowledge about this enabling technology. Results of this study showed that Swiss citizens had a neutral attitude toward nanotechnology – they were neither enthusiastic about the technology, nor were they rejecting it.

Lay people differ in their acceptance of nanotechnology, and trust seems to be a factor that influences how lay people assess nanotechnology applications [64, 66, 67]. Participants having trust in the industry and in regulatory agencies assessed the nanotechnology application more positively than participants not having trust. The importance of naturalness seems also to be a factor that can affect the perceived risk and the perceived benefit of nanotechnology foods and nanotechnology food packaging [67]. It is likely that general perception of technological progress and attitudes toward technology shape attitudes toward nanotechnology. People often use such convictions in assessing new technologies, about which they have little knowledge [70].

Lay people may have difficulties in understanding the size scale and symbolism of nanotechnology [71]. It should be noted, however, that there may be no need for lay people to understand the principles of nanotechnology in order to accept or to reap the benefits of nanotechnology. The importance of lay people's scientific knowledge must not be overstated. Most people could not explain how a car works. Nevertheless, they drive a car and are willing to accept this technology.

The problems associated with the introduction of genetically modified products in some countries raise the question whether nanotechnology food products may be faced with the same difficulties. It has been argued that GM and nanotechnology are quite different food technologies, and therefore no premature generalizations should be made [72]. Genetic modification that involves the insertion of genes from another species produced a large drop in perceived naturalness [73]. The idea of tampering with nature [74] seems to be an important reason why some people are hesitant to accept GM technology. Since for most people nanotechnology foods will not be perceived as tampering with nature, few people will be opposed to nanotechnology on moral grounds [72].

12.4.2
Scientists and Industrial Perspective

Scientists in the field of nanotechnology are in general more optimistic about the potential benefits and less concerned about the risks of this technology than the public [64, 75]. The study by Scheufele and colleagues [75] suggests that most experts expect that nanotechnology may lead to a better treatment of human diseases and improved ways to clean up the environment. Scientists were more concerned than the public that nanotechnology may lead to more pollution and environmental contamination and new health problems.

Lay people and experts assess the risk associated with nanotechnology differently [64]. Lay people tend to perceive higher risks associated with nanotechnology applications than experts. Another study also found that, for most risks associated with nanotechnology, lay people perceive more risks than experts [75]. However, regarding the risk of more pollution, experts expressed more concern than lay people. This result fits well with the outcomes of the studies discussed in the previous section. It seems that lay people are not especially concerned about a possible impact of nanotechnology on the environment.

Results of an industry survey in Switzerland and in Germany raises some doubts whether all companies properly address possible risks associated with nanotechnology [23]. The way lay people perceive nanotechnology food applications, in conjunction with an industry that may not address the risks associated with a technology as expected by the public, may lead to a social amplification process [76]. Applications in the food or health domains are associated with a high level of dread and distrust [64]. As a result, such nanotechnology applications are most likely to become controversial topics.

12.5
Conclusions

The release of nanoparticles can occur at every stage of the life cycle of a product. Analysis of the life cycles and research about possible effects of nanoparticle products on the environment are still in their infancy. Therefore, it is still unknown in which stages of the life cycle of a product it is most likely that nanoparticles enter the environment. Humans may be confronted with nanoparticles in food through various pathways. Based on the results of available studies, it is still unclear if nanoparticles are problematic for human health and the environment and if nano-food should be treated separately.

Most lay people know very little about nanotechnology, and most people do not have strong attitudes toward this new technology. This poses a problem for studies dealing with lay people's risk perception. People may not be able to answer questions without receiving further information. However, providing additional information may influence people's attitudes in a certain direction. It is difficult to forecast how the public will react to nanotechnology in the future. Based on available risk perception research, it seems that lay people are less concerned about environmental problems associated with nanotechnology, but mainly with nanoparticles that are consumed with foodstuff.

Nanotechnology is an enabling technology, and it is used for a heterogeneous set of applications like ammunition, car paint or foodstuffs. Incidents in one domain may have spill-over effects on other domains. A problem in one field of applications may be extrapolated to other applications because the same label "nanotechnology" is used. This is similar to what has been labeled as "guilt by association" [77]. The industry may be well advised, therefore, not to emphasize nanotechnology in marketing their products.

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