A Review of Nanotechnology Experiments with Environmental and Biological Applications

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Abstract

Nanotechnology has the potential to revolutionize medicine and improve human health. New nanomaterials can negatively affect the environment. Biology provides the key to securing these benefits while avoiding unwanted outcomes. Educating current students about the biological applications and environmental impacts of nanotechnology is necessary so that they can join the technological workforce of the future and make informed decisions as citizens about how to use nanotechnology. After a brief introduction to nanotechnology, we review nanotechnology experiments which highlight biological applications or illustrate the effects of nanotechnology on living organisms. These experiments are most appropriate for high school and college students. Educators will find this review useful for discovering new and interesting hands-on activities for their students.

Introduction to Nanotechnology

Everything that chemists synthesize in their laboratories and everything made by nature exists as atoms, each belonging to one of about 100 different elements. Until recently, anything new had to be made by mixing different combinations of atoms of these elements. Given the millions of possible combinations of atoms, one would think that this could satisfy our need for innovative materials. Recently, scientists discovered a new way to make well-known elements perform new tricks.

Our everyday experience tells us that a piece of gold has a yellow color. But if you divide it in half, and keep dividing it into smaller pieces, smaller than a grain of sand, smaller than a bacteria cell, and even smaller, gold begins to change. When size of the piece of gold is less than 100 nanometers ($100X10^{-9}$ m), it changes color, melting point, chemical reactivity, and other properties. At the nanoscale, properties change with the size of the particle. If scientists can control the size of the particles, then they can control the properties of the particles, leading to an element behaving differently depending on the size of the nanoscale particles (nanoparticles). Entire industries, such as electronics, are undergoing a revolution in their ability to offer new products at lower prices, higher quality, and greater functionality. Because of the many new features of nanosized materials, nano-enabled technology, or nanotechnology, there is an opportunity for our society to undergo another technological revolution, similar to the industrial revolution several hundred years ago and like the information technology revolution more recently (Roco, 2003a; Roco, 2003b).

Nanotechnology and Biology

Doctors may use nanoparticles in many ways to improve our health. The size of gold nanoparticles allows them to enter small spaces, such as within a patient's cancer cells. Once there, a doctor can heat the gold particles with radio waves, causing the cancer cell to decompose (Cherukuri & Curley, 2010). By using nanosized sensors, doctors can take diagnostic measurements more quickly and easily – a drop of blood from a pinprick replaces the need to draw blood from a patient's vein.

Since nanoparticles possess unique characteristics, there is justifiable concern that they could negatively affect our environment. What happens to flora and fauna in the event of an accidental release of nanoparticles into a river? The fate of nanoparticles depends not only on their size and composition but also the coating that surrounds the particles. Nanoparticles are often covered in a layer of other chemicals. This coating prevents them from sticking together and forming large, bulk particles with a loss of their unusual properties. Nanoparticles may agglomerate and precipitate, removing them from the water and accumulating in sediment. Coated nanoparticles may remain unreacted until environmental conditions change, such as when fresh water flows into an ocean. Certain aquatic plants can absorb nanoparticles readily, helping to filter them from the water. Harvesting these plants, known as phytoremediation, can be an effective way to remove nanoparticles or other toxins from the natural environment. Some plants or animals may have a low tolerance for particular types of nanoparticles, requiring an immediate intervention. Engineers and scientists, including the authors, are studying how nanoparticles affect the environment and how to minimize the harm caused by their release.

Nanomaterials are not only a man-made phenomenon. Many examples of nanoscale features exist in nature, including iridescent butterfly wings, structures of sea shells, sticky feet of the gecko, and water repellent surfaces on lotus leaves. With the tools used to analyze nanomaterials, scientists can now more fully understand how these plants and animals behave. They are beginning to design materials with similar features observed in nature (biomimicry). Of course, the molecules and processes within biological cells are the ultimate nanomachines, capable of synthesizing chemicals that are not reproducible in the laboratory. Nature can also contribute to nanoparticle synthesis. Scientists have discovered a wide variety of naturally occurring materials which provide inexpensive, environmentally sustainable, and easy to use ingredients for making nanoparticles.

Biological Nanotechnology and Education

Nanotechnology will affect the health and well-being of everybody and our natural environment. In order to minimize the adverse effects and promote the benefits of nanotechnology, students need to learn about nanotechnology in school. This will not only increase the number of future scientists with hands-on experience and knowledge of nanotechnology, but it will also create a well-informed public, capable of making decisions about how to use nanotechnology. This is a global challenge that involves educators on every continent. See a recent book, Global perspectives of nanoscience and engineering education (2016) to learn more about how nanotechnology is taught around the world and a chapter in the forthcoming 4th edition of the Spring Handbook of Nanotechnology (Winkelmann & Bhushan, 2017).

Education can take many forms. Students in primary grades can become familiar with the basic concepts of nanotechnology, such as size and scale, both those familiar to them as well as micro- and nanoscale objects too small to see with the unaided eye. As students enter secondary school, they can learn about nanotechnology in physics, biology, and chemistry classes. Many teachers feel that they do not have time in their busy curriculum schedules to add additional topics like nanotechnology. They can only add an activity if it specifically addresses the course's existing learning objectives. Given the multi/interdisciplinary nature of nanotechnology, this is frequently possible (Stevens, Sutherland, & Krajcik, 2009).

Nanotechnology curriculum materials are often designed for use in higher education classes, where the curricula are more flexible. Schools offer academic minors, majors, and certificate programs in nanotechnology (Nanoscale science and engineering education 2008; Global perspectives of nanoscience and engineering education 2016). Students may learn about individual nanotechnology topics within existing courses or in separate nanotechnology courses. The advantages of this approach are that no new classes need to be created and students learn about nanotechnology within the context of the course subject. An alternative is to create one or more separate courses specifically about nanotechnology. Students gain a deeper understanding of topics presented in those classes and if one course is successful, another nanotechnology course can be added to the curriculum. While most nanotechnology courses are designed for graduate school or undergraduate capstone experiences, some schools offer nanotechnology as early as the first year.

As an example, Florida Institute of Technology has taught a unique introductory nanotechnology laboratory course for over ten years (Winkelmann, Mantovani, & Brenner, 2008; Winkelmann, 2009a). Students perform a wide variety of experiments and gain hands-on experience using education-grade scanning tunneling and atomic force microscopes (STM and AFM). Many of the experiments are designed by the faculty who team-teach the course. Other experiments are adopted from those in the published science education literature. Topics include the design of solar cells, effects of nanoparticles on plants and bacteria, and engineering applications of nanoparticles. Students also learn about broader societal issues, such as the ethical use of nanotechnology. In that activity, students role-play characters involved in a debate about using nanotechnology to solve a problem in their community (Winkelmann, 2012). Lab experiments in the course are designed for students who have completed just their first semester of general chemistry.

Other schools offer classes with a greater focus on engineering, biology, chemistry, or physics. Students at a liberal arts school can learn about the way nanotechnology affects society (Porter, 2007) or the overlap between disciplines of nanotechnology and art (Bentley & Imatani, 2012).

Nanotechnology education resources are freely available (Winkelmann, Bernas, & Saleh, 2014) and nanoparticle synthesis experiments are reviewed elsewhere (Winkelmann, 2009b). The focus of this review is on nanotechnology experiments which also involve an aspect of biology or environmental science. The experiments described below can fit within a single nanotechnology laboratory course or they can be added to traditional science laboratory courses. Experiments could be altered to serve as classroom demonstrations or outreach activities. We have performed and taught most of the experiments described below.

Equipment and Safety

Many of these experiments are designed to be taught at the introductory level but could be simplified for teaching in a high school science course. Necessary equipment and safety issues may restrict the implementation of some experiments.

Color is an important property of nanoparticles due to the unusual way that it changes with particle size. The peak in an absorbance spectrum of a nanoparticle solution will shift to shorter wavelengths as the particle size decreases. Thus, it is a reliable estimation of the most common size of the nanoparticles. The width of the peak is also noteworthy because it indicates the range of nanoparticle sizes formed. A UV-visible spectrometer is a useful tool for quantitative absorbance measurements but a research-grade instrument is unnecessary. Education-grade spectroscopy instruments are appropriate, as are even less expensive colorimeters. The most economical method is comparing the nanoparticle solution color to standards. This approach is effective, for instance, for measuring the concentration of gold nanoparticles in dietary supplements (Campos et al., 2016).

Education-grade STM and AFM instruments can exceed the teaching laboratory budgets of many schools. Some research institutions offer remote access or remote viewing of these instruments and the images they collect. Many websites contain a catalog of these images for viewing any time. Other low-cost approaches which provide hands-on simulations of these microscopes include Lego models (Lindell & Kähkönen, 2013; Schwenz & Pacheco, 2014) and other hands-on activities (University of Wisconsin - Madison MRSEC Education Group, 2016).

Other advanced characterization techniques, such as transmission electron microscopy (TEM), and dynamic light scattering (DLS) can be used to characterize the nanoparticles. Use of these instruments can change an experiment designed for a first-year course into an upper-level laboratory activity.

Safety is always a paramount concern in the laboratory. Chemicals, biological specimens, and nanomaterials pose their own individual safety concerns. For all experiments described in this chapter, it is assumed that students will wear appropriate eye protection and laboratory coats or aprons. Gloves are recommended. Instructors should read all safety information for the materials they are handling and make students aware of all hazards. When working with bacteria, use non-infectious strands. Nanoparticles are more hazardous when in the solid phase compared to the solution phase. Powders can more easily enter the body through the lungs. Unless absolutely necessary, the authors recommend leaving nanoparticles dissolved in solution. Follow all regulations when disposing of chemical and biological waste.

Synthesis of Nanoparticles Using Natural Products

Metal nanoparticles, especially those of gold and silver, can easily form by reducing metal cations with a wide variety of organic and biological reducing agents. Proteins, amino acids, carbohydrates and natural products react with metal cations to form nanoparticles with different sizes, shapes, and morphologies. Often, the reductant coats the nanoparticles, increasing their stability through electrostatic or steric repulsion. Most of these synthesis methods are designed to be completed in a two- or three-hour lab period, and can be adapted to the high school classroom as needed. The syntheses are considered to be examples of green chemistry, as the methods used to make nanoparticles use renewable materials and aqueous solutions at low temperatures.

Silver nanoparticles can form using tea, coffee, honey, juice, wine, and vinegar in introductory undergraduate labs, including courses for non-science majors (Metz, Sanders, Miller, & French, 2014). Students react small volumes of silver nitrate with one of these reductants at room temperature. The reaction is complete after 30 minutes so students can measure the absorbance spectrum of the nanoparticles. Particle size is typically 50 - 75 nm in diameter and the solution has an absorption peak between 445 and 480 nm, depending on the reductant used. A similar, upper-level undergraduate synthesis of silver nanoparticles with honey is also described (Paluri et al., 2015). A dilute solution of honey is heated with silver nitrate, stirred for 30 mins and the absorbance spectrum is recorded. The peak wavelength is 420 - 440 nm.

Gold nanoparticles form using tea leaf extractions as a reducing agent (Sharma, Gulati, & Mehta, 2012). Tea leaves are extracted in water by stirring vigorously then filtering. Tetrachloroauric(III) acid is added to the solution and within 15 mins, the solution turns purple, indicating the formation of gold nanoparticles. The gold nanoparticles are 20 - 25 nm in diameter and exhibit an absorbance peak at 530 - 563 nm. An upper-division undergraduate adaptation of this procedure uses inquiry-based learning to compare green and non-green syntheses of silver and gold nanoparticles (Paluri et al., 2015).

Plant leaves can also reduce gold and silver cations to nanoparticles. An undergraduate lab procedure describes the reduction of silver by geranium leaves (Richardson et al., 2006). Geranium leaves are cut up and briefly boiled in water, then the solution is centrifuged and filtered. A small volume of extract is added to a silver nitrate solution and heated. The particles have an absorbance peak at 415 nm. Particle diameters range from 15 to 45 nm. The lab is designed for high school or first-year undergraduate students.

Impact of Nanoparticles on Microorganisms

Silver nanoparticles are commonly used as antimicrobial and antibacterial agents. Experiments demonstrate the toxicity of silver nanoparticles and show their medicinal applications. Students synthesize silver nanoparticles using common reduction methods and expose these particles to yeast cells or bacteria cultures. These experiments are designed for high school chemistry and biology classes or first year undergraduate lab courses.

In a high-school level biotoxicity experiment, students synthesize silver nanoparticles using a sodium citrate reduction method (California NanoSystems Institute, 2012). Silver nitrate and sodium citrate solutions are mixed and heated until a faint yellow color is observed, indicating that very small silver nanoparticles are forming. The particles cool to room temperature and the UV-visible spectrum is recorded. The solution has a peak absorbance around 410 nm and the nanoparticles are 4 nm in diameter. Solutions are prepared containing water, silver nanoparticle solution, and dextrose in a filtration flask. Baker's yeast (Saccharomyces cerevisiae) powder is added to the flask then the flask is sealed with a stopper. A hose connects the flask to an inverted graduated cylinder in a bucket of water (figure 1) or a manometer, which is used to measure the volume of carbon dioxide released by the yeast. Silver nanoparticles are toxic to many types of organisms so there is a change in the rate of cellular respiration when silver nanoparticles are present. The volume of carbon dioxide released is measured for 30 mins. Students can conduct a control experiment using no silver nanoparticles to observe the respiration of healthy yeast cells.

Additional studies of silver nanoparticle biotoxicity using the yeast respiration experiment were performed by our group. We prepared silver nanoparticles using other common reduction methods found in the literature. Nanoparticles

Figure 1: Arrangement for silver nanoparticle-baker's yeast biotoxicity experiment.

with different coatings and sizes were tested, including 12 nm particles coated with borohydride (Mulfinger et al., 2007), 40 nm particles prepared via the Tollens reaction (Soukupova et al., 2010), and a silver colloid claiming to contain 1 - 10 nm silver particles coated in a protein sold by Natural Path Silver Wings. None of the nanoparticles had any significant effect on the yeast respiration, indicating that silver nanoparticle toxicity is dependent on the size and coating of the particles with the smallest citrate-coated nanoparticles being the most effective. Thus, while many methods exist to make silver nanoparticles, only the citrate reduction method formed silver nanoparticles which show any efficacy towards the baker's yeast. It was also observed that high silver cation concentrations are toxic to baker's yeast.

Silver nanoparticles can also slow or prevent bacteria growth. Students can prepare cultures with bacteria and exposed them to silver nanoparticles. Results are evident within one week (Gardner & Jones, 2009). Petri dishes are prepared with agar nutrient broth beforehand. Students collect bacteria colonies from common household places for both treatment and control plates. Instead of synthesizing nanoparticles themselves, students swab the plates with a silver nanoparticle-coated metal hook, called a handler, which is used in place of a hand to touch bacteria-contaminated surfaces (e.g., toilet handles and door knobs). Plates are incubated for one week and the number of colonies on the treatment and control plates are counted and compared. The nanoparticles which rubbed off of the handler's surface onto the agar cause a significant decline in bacteria population. This experiment is especially appropriate in cases when chemicals or laboratory equipment is not available.

A high school level lab experiment introduces students to silver toxicity by exposing E. coli and Baker's yeast to silver nanoparticles (National Nanotechnology Infrastructure Network, a). The experiment requires three class sessions, including a day to prepare practice plates using gelatin. The teacher prepares a silver nanoparticle solution and petri dishes with agar in advance. The students prepare control plates for each microorganism, as well as diluted silver nanoparticle solutions. Plates are incubated for up to two days at room temperature or for one day at 37 °C. The students analyze their results in groups and discuss the effectiveness of silver as an antimicrobial agent.

Similar high school experiments can be performed in 3 or 4 class sessions to demonstrate the effects of silver on bacteria species. The teacher prepares agar plates in advance. Students synthesize silver nanoparticles in class then expose E. coli to different concentrations of silver nanoparticles in duplicate, and count the numbers of colonies growing on agar plates (National Nanotechnology Infrastructure Network, 2012a). The students also expose plates to soap and other common disinfectants to compare the effectiveness of silver nanoparticles versus household cleaners. These results are compared to the control solutions, grown in media broth.

Silver is used in bandages as an antimicrobial source. Students can compare the effectiveness of bacteria growth on bandages (National Nanotechnology Infrastructure Network, b). Bacteria (Micrococcus luteus or Staphylococcus epidermis) are exposed to bandages without silver, and students create the following treatment groups: a control, a treatment with a common disinfectant, and a silver nanoparticle treatment (synthesized by students or purchased from a commercial source). A commercially available bandage manufactured to contain silver particles is also studied. Students cut the pads out of the bandages and place them in a petri dish. Then, students use a cotton swab to spread bacteria around the plate and incubate the plates for one day at 37 °C. Students measure the zone of inhibition around the bandage and record data and observations.

A similar experiment can be performed with socks, in which students prepare silver nanoparticles by a sodium citrate reduction method then cut 5 cm square pieces of socks and soak in solutions of silver ions, nanoparticles, or other disinfectants (National Nanotechnology Infrastructure Network, c). These socks are then placed in petri dishes (prepared by the teacher) and students add bacteria to the plates. The plates are incubated for a day at 37 °C and students observe inhibition of bacterial growth the next day.

Impact of Nanoparticles on Plants

The impact of silver nanoparticles can be examined in both aquatic and terrestrial plant life. Experiments are designed for high school and first-year undergraduate students to showcase the negative effects of nanoparticles. A second part to the silver nanoparticle synthesis using juice, wine, coffee, etc. discussed previously demonstrates the effects of silver nanoparticles on a terrestrial plant, Wisconsin Fast Plants (Brassica rapa) (Metz et al., 2014). Potted plants were exposed to nanoparticle solutions multiple times per week for up to one month. Students measure the plant heights every few days. The plants are then digested in concentrated nitric acid and inductively coupled plasma instrumental techniques are used to determine the amount of silver absorbed by the plants. Results show that nanoparticles formed using various food ingredients as reductants have varying effects on plant growth.

A similar experiment demonstrating silver nanoparticle toxicity has been developed for high school students by exposing fresh water plants (Elodea or Egeria sp.) to commercial colloidal silver (National Nanotechnology Infrastructure Network, 2012b). Students expose the plants in test tubes with water (no soil) and solutions of colloidal silver for a day and make observations during the next class period. Students can also synthesize silver nanoparticles in class and expose the plants to them. Our group has developed a similar lab experiment for first-year undergraduate students by growing Egeria densa (Brazilian Elodea) in silver nanoparticle solutions. Silver nanoparticles are synthesized using a citrate reduction method and characterized using UV-visible spectroscopy (California NanoSystems Institute, 2012). Particles are 4 nm in diameter and coated with citrate ions. Stalks of E. densa are grown in large test tubes with dilute silver nanoparticle solutions for 1 week in a greenhouse. The stalks are then dried in an oven and leaves are removed from the plant. The leaves are ground in cold ethanol and a UV-visible spectrum is recorded to calculate chlorophyll a and b concentrations (Lichtenthaler, 1987). In experiments run with silver nitrate controls, the silver cations showed a greater impact on the plants compared to the same concentration of silver nanoparticles.

Nanosized silver is by no means the only material which can harm plants. In a simple experiment designed for high school and undergraduate students, engineered nanoparticles of SiO2 and ZnO are added to a dish containing water and mung beans (Ross, Owen, Pedersen, Liu, & Miller, 2016). Both compounds caused a noticeable lack of growth in the beans, with the zinc oxide nanoparticles showing the greater toxicity. Beans kept in a dish of water sprouted significantly longer stems and more leaves. Students can see differences in the rate of growth after less than one week. No instrumentation is necessary for the experiment; students simply measure the length of the stems using a ruler. To learn more about the nanoparticles, students also receive an image of the particles collected by a scanning electron microscope (SEM) then use imaging software to measure the range of particle sizes. By seeing the small sizes of the nanoparticles, students can begin to understand how the nanoparticles enter the bean and affect its growth.

Impact of Nanoparticles on Animals

The impact of nanoparticles on animals can be assessed using viability assays to determine mortality after exposures for 24-72 hours. Students start with an initial number of organisms in an ecosystem and expose them to nanoparticle sources, count the number that are no longer viable over time, then report this data. Silver sources can be purchased from suppliers or students can synthesize silver nanoparticles using common procedures such as those previously mentioned.

Copepods (Daphnia sp.) are a common freshwater crustacean used in toxicity tests. Students can expose copepods to different concentrations of silver nanoparticle solutions and perform viability tests over a 3-day period (Centre for Mathematics, Science and Technology Education, 2016). The effects of silver nanoparticles, micron-sized silver particles, and silver cations can all be studied. Students can also calculate the LD50 (concentration of silver which is deadly to 50% of the population of organisms).

Similar to the copepod experiment, highs school students can expose California blackworms to different concentrations of commercial colloidal silver to determine viability (National Nanotechnology Infrastructure Network, 2012b). The experiment measures the toxicity of silver after a 24 hour period and provides teacher resources for a 3-day lesson about the ecosystem and aquatic food chain.

A third experiment exposes synthesized silver and gold nanoparticles to brine shrimp for an interdisciplinary science lab that can be used for high school or first-year undergraduate courses (Maurer-Jones et al., 2013). Students can synthesize gold nanoparticles through a sodium citrate reduction and silver nanoparticles through a sodium citrate or sodium borohydride reduction. Alternatively, the instructor can prepare stock solutions of nanoparticles and students can dilute those. Students expose the brine shrimp to different concentrations of nanoparticles in well plates over a 24 hour period. The percent viability is then measured based on shrimp moving when exposed to a light source. The teacher instructions provide a way for students to expose shrimp for two to three days in an inquiry-based experiment.

Nanoparticles as Biosensors

The reduction of metal cations to nanoparticles can be used to observe different biological processes based on the redox reactions involving biomolecules. For example, gold(III) ions are reduced to gold nanoparticles by hydrogen peroxide in the oxidation of glucose by the enzyme glucose oxidase (Bai et al., 2009). The reduction of gold can be measured at 540 nm. The peak intensity is proportional to the enzymatic activity. Students also measure the change in the concentration of the nanoparticles with respect to different concentrations of either glucose or hydrogen peroxide. This experiment is suitable for analytical chemistry courses because students use a standard curve to measure glucose concentration and determine the molar absorptivity of the glucose sensor.

Measurement of glucose in blood can be adapted for a high school biology or chemistry experiment (National Nanotechnology Infrastructure Network, d). Students measure the glucose concentration in synthetic blood and urine samples using blood glucose monitoring kits. Commercially available kits include the necessary materials for measurements, including glucose standards and test strips. The teacher must prepare different glucose solutions to simulate urine and blood, using food coloring. The glucose meter measures a fluorescence signal from carbon nanotubes, which should be explained to students when introducing the experiment.

Nanoparticles in Land and Water

High school students can create models using clay to demonstrate how easily nanoparticles migrate from land to the ocean and waterways (National Nanotechnology Infrastructure Network, e). Using commercial water testing kits, students measure pH, nitrates, ammonia, and nitrites in DI water. Students create a clay mountain in large tray, and add fertilizer to simulate nanoparticles. Water is then pipetted down the mountain, into the tray, demonstrating runoff. The students then measure the properties of the contaminated water, simulating the effects of nanoparticles, and indicate differences in water quality. The lab can be followed up with experiments demonstrating the toxicity of nanoparticles to aquatic and terrestrial life, including plants and animals (National Nanotechnology Infrastructure Network, 2012b).

Nanotechnology plays a role in cleaning a contaminated environment. Iron nanoparticles can reduce water pollutants while the iron is oxidized to rust. Students can synthesize iron nanoparticles by reducing iron chloride in the presence of sodium borohydride (Winkelmann et al., 2011). The nanoparticles are stable long enough for students to mix them with a dye, which represents the pollutant. Students monitor the solution's absorbance as the color fades. A graph of absorbance vs. time reveals the rate of the reaction. Students can also react the dye with micron-sized iron particles to see how the particle size affects the reaction rate. Larger particles have less surface area per gram so the reaction proceeds more slowly. While a faster reaction is typically more desirable when cleaning the environment, students might also consider the cost, time, and effort involved in preparing the nanoparticles. Larger particles are less expensive. There are tradeoffs to consider, leading to no clear, correct answer but this creates a realistic scenario involving the use of nanotechnology.

Nanotechnology and Biomimicry

Many biological systems have nanoscale adaptations that help them survive. For example, sharks have a nanoscale pattern on their skin that acts as an antifungal and antibacterial agent. Another example of nanoscale adaptions is seen in lotus leaves, which have a hydrophobic coating that allows the leaf to repel water. A high school lab experiment demonstrates that commercially available materials possess the same hydrophobic properties as biological organisms, which makes the surface self-cleaning in aquatic environments (TeachEngineering, n. d.). The experiment compares the plant leaf to a nano-fiber cloth that mimics the process occurring on the lotus leaf surface. Students can scratch or cut the cloth and evaluate its performance.

Conclusions

Nanotechnology is a broad, interdisciplinary field that yields a wide range of applications in electronics, medicine, consumer goods, construction materials, agriculture, and others. As with any technology, we should weigh these benefits against issues related to its sustainability and environmental impact. Since many new uses of nanotechnology will be developed in the near future, today's students must learn about nanotechnology and how it affects the world around us. This will not only inspire the next generation of scientists and engineers but also create a scientifically literate general public who will choose how they want to use nanotechnology.

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