Nanotechnologies for water sustainability

A Roadmap for Deployment of Nanotechnologies for meeting Water sustainability challenges in Latin America

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This roadmap is addressed to stakeholders dealing with nanotechnologies for water in Latin American countries. Considering the newness of the field and the early development stage of applications, the recommendations found here are more directed to policy-makers, academic experts and other experts dealing with knowledge transfer from university or research institutes to industry and public utilities and the water intensive industry, such as mining and agro-food. The present roadmap is the product of a 2-year multi-stakeholder research process in which we addressed the question of how nanotechnology based solutions to water related challenges (especially focusing on the Latin American context) could be produced in the future and made available to society. The research process approached five thematic clusters: (1) research, (2) policy making and funding, (3) education and training, (4) industry and investment and (5) ethical, legal and social aspects. The water applications focused on are potabilisation of water (chemical pollutants and disinfection), innovative solutions for desalination for drinking and process water and waste water treatment with recovery aspects. The roadmap focus on applications, research and development and gives recommendations for implementation considering the time horizon up to 2030 and considering efficient and responsible management of technological solutions.

From a global average perspective, Latin America is water-rich. With 500 million inhabitants or 8% of the world population distributed in 20 countries, the region possesses 31% of the freshwater resource in the world. However, this water is not equally distributed, 38 million people –nearly 7% of the population– are without access to safe water. Climate change can dramatically worsen the situation.

For example, Bradley et al. [1] present data on the effect of melting glaciers, especially in Southern Andes. As many large cities and irrigation systems in the Andes depend almost entirely on high-altitude glacier water stocks to complement rainfall during the dry season. As these water resource buffers shrink, further alternative water supplies may become very expensive. Less water intensive agricultural practices need to be installed and solutions for water recycling developed.

To illustrate the need for innovative water solutions we have viewed the typical water management situation in a few Latin American countries. In Mexico, water scarcity is regarded as significant [2]. By sector, agriculture accounts for 77% of water use, industry 10% and domestic uses account for 13%.

Although agriculture represents the largest consumer, almost half of Mexico's irrigation districts is said to be in a state of slow deterioration and leakages, leading to inefficient usage of water. Almost 70% of the country's water is extracted from underground aquifers, with a rate of extraction far exceeding replenishment, and several of them in the northern regions are affected by natural arsenic and fluoride contamination.

Continual draining of water from such aquifers have resulted in Mexico City sinking 10 metres in the past century [3], clearly indicating that solutions for water saving and reuse are required. Industrial end users in Mexico include many sectors, namely: oil and gas, mining, petrochemical, pulp and paper, food and beverage and chemical industry.

According to Frost and Sullivan's report

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[4], many industries have taken the decision to recycle water as a socially responsible action, and when water has an increasing price, many industries have chosen to install their own water treatment plants. The consequence of this is that the volume of treated water has doubled during the past 10 years. Still, in total, only 36 % of wastewater is treated [4].

Argentina has one of the highest levels of per capita water usage in the world at around 500 l/day [5]. Averagely the availability of water outstrips demand, yet 11% of the popula-tion still lacks piped water [6]. In contrast, yearly withdrawal capacity is 994 km^3, and con-sumption is 745m^3 a person annually, more than three times the average of Brazil. Nevertheless, and not everyone in Argentina benefits from a good water supply. Areas in the North of the country, and in the poorest and most populous districts on the periphery of Buenos Aires, have little access to water. StillAgain, Central Argentina is the area most affected by arsenic contamination in the world [7].

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In Chile only 4% of water withdrawals are used in the municipal sector, whereas agro and aquaculture accounts for 83%; industrial use accounts for 13%, of which 5,6% is used by the mining industry [8]. Industrial pollution is an issue both in Central and Northern regions of Chile and very often these discharges go untreated directly into river basins, lakes and irrigation channels. The impact of the mining industry is especially noted in the north, which is also an area highly affected by arsenic contamination [7].

General applications of nanotech-nologies for water fall under remediation of polluted water, po-tabilization of water, desalination and nanodevices (sensors for water quality monitoring). The benefits from the use of nanomaterials may derive from their enhanced reactivity, surface area, and sequestration characteristics. A variety of nanomaterials are in various stages of research and development (R&D), each possessing unique functionalities that are potentially applicable to the remediation of industrial effluents, groundwater, surface water and drinking water.

United Nation's forecasts are quite alarming regarding the availability of drinking water in the future. It is foreseen an increase in the number of the world population affected by water scarcity, which is already around 40%, when by 2050 at least one in four people are likely to be affected by recurring water shortages. Deployement of nanotechnologies for water in Latin America, as well as all over the world and especially in water scarce regions and lacking of proper sanitation, could help to achieve the targets of the United Nation's Sustainable Development Goals. According to United Nation's whose Goal Number 6 aims to "Ensure access to water and sanitation for all". Adequate policy actions in Latin America, following for example, the recommendations of the roadmap presented in this document, would set the examples needed for other regions of the planet.

Research Methods

The research process that culminated with the formulation of the roadmap for the deployment of nanotechnologies for water in Latin American countries, was carried out during the two year long project NMP-DeLA (Nanosciences, Nanotechnologies, Materials and New Production Technologies Deployment in Latin American Countries). It included desk research, bibliometric analysis and expert consultation through questionnaires, interviews, focus groups and panel discussions. Desk research was carried out in order to gather information on applications of nanotechnologies in the field of water and a bibliometric study, which provided information on the state-of-the-art of projects, most active institutions and researchers, and initiatives and enabling policies in Latin America.

Qualitative methods, such as consultation with experts from academia, industry and policy making, have been applied to analyse how much of current nanotechnology developments for application in water can deployed and what issues need to be addressed. Interpretation, discussion and validation of the first results of desk research and roadmap were performed with experts and the wider stake-holder community in the framework of NMP-DeLA events. These events consisted of two expert work-shops on water and energy, one held in November/2014 in Monterrey/Mexico (together with a summer school) and another held in brazil in 2015 and online consultation.

Following we present the findings of the applications of nanotechnologies for water with relevance for Latin America, the results of the bibliometric study and the roadmap, which was compiled during the process of research.

Nanotechnology for water with relevance to Latin America

Following is an overview of the state of the art and drivers, challenges and opportunities related to nanotechnology for water taking into account their relevance in Latin American countries.

Drinking water production (potabilisation)

Depending on the quality of the raw water, production of drinking water requires different steps using a combination of physical, chemical, physico-chemical and/or biological processes. Generally, surface waters require more comprehensive treatment than groundwater.

Potabilisation aims at removing organic matter, hazardous chemical pollutants, (including organic and inorganic compounds), bacteria and viruses from the water. A typical set of processes comprises screening for the removal of large floating items, coagulation or flocculation of organic matter, filtration to remove particles and bacteria, activated carbon filters to remove smell, taste and colour, advanced filtration for disinfection and chlorination.

Fine filtering using membrane technology, is also a possible option for advanced treatment of surface water for drinking water production. Membrane properties important for the operator of a water treatment plant are 1) high rejection of dissolved organics, 2) low salt rejection, 3) low energy consumption and 4) stable performance after repetitive cleaning. For a potable water treatment plant, in order to be economically and operationally successful these four criteria have to be met.

As membrane processes are considered key components of advanced water purification and desalination technologies, there is a continuous search for new materials that are more selective and less prone to fouling. Incorporation of catalytic or magnetic nanoparticles into membranes derives highly efficient filters for the removal of chemical and microbiological impurities from drinking water that can also be used to lower the energy requirement of membrane filtration by adding antifouling qualities to the membrane.

In this regard, nanomaterials (e.g., carbon nanotubes, nanoparticles and dendrimers) are contributing to the development of more efficient and cost-effective water filtration processes (Table 1).

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Bioactive nanoparticles are playing an important role in water disinfection. Contamination from bacteria, protozoans, and viruses is possible in both ground and surface water. A variety of strong oxidants such as chlorine are normally used as disinfectants for pathogens in water treatment. However, these compounds tend to generate toxic by-products, such as trihalomethanes, haloacetic acids and aldehydes; so alternative disinfectants are also needed. Ozone (O_3), instead, does not have any residual effects, but produces unknown organic reaction products. For ultraviolet disinfection, longer exposure time is required for effectiveness, but there is no residual effect.

Several types of nanomaterials, such as silver, titanium oxide, magnesium, zinc and chitosan are capable of inactivating waterborne disease-causing microbes and viruses. Due to their charge capacity, they possess antibacterial properties. TiO_2 photocatalysts and metallic and metal-oxide nanoparticles are among the most promising nanomaterials with antimicrobial properties. A significant research effort continues to understand the mechanisms and enhance the efficiency of nanomaterials as antimicrobial agents [10].

Table 1. Examples of nanostructured and nanoreactive membranes for use in water purification.

Membrane	Pollutant
Nanostructured membrane, Carbon nanotubes	Bacteria and viruses
Nanoreactive Alumina membrane formed from A-alumoxane	Synthetic dyes
Functionalized Alumina membranes	Divalent cations (e.g. Fe2+, Hg2+)
Silica and cellulose-based membranes functionalized with amino acid homopolymers	Metal ions
Alumina or polymeric membranes with gold nanoparticles	4-Nitrophenol
Polymer-impregnated ceramic TiO2 filters	Polycyclic aromatic hydrocarbons (PAHs)
Polymer-impregnated ceramic alumina and silicon-carbon filters	Trihalomethanes, PAHs, pesticide
Nanosilver impregnate membranes	Bacteria
Ag/TiO2 nanofibre membrane	Bacteria
TiO2/Al2O3 composite membranes	Direct Black 168 dye
TiO2 photocatalytic nanofiltration membrane	Methyl orange, azo-dye

Source: Modified from Mohmood et al. [9].

Industrial waste water treatment and decontamination (remediation).

Oil and gas and mining industry are two water intensive sectors with high relevance in Latin America and water treatment is quickly emerging as one of the most significant challenges facing, for example the oil and gas industry. With large volumes of water used in the oil/gas production process, water is increasingly moving from an operational issue to one of strategic significance.

Nanomaterials for the remediation of water in the oil and gas industry should have a high sorption capacity for heavy metals, oil and other organic matters. Furthermore, in order to be economically feasible, the nanomaterial need to be easily recovered after wastewater treatment and cleaned for re-use. For example, porous boron nitride nanosheets have been reported to have potential for effective cleaning of oil mixed wastewater [11].

In the case of mining industry, today most applications of nanotechnology in mine water remediation have essentially followed the general application of nanomaterials in wastewater treatment and purification. Most research in this area has been performed at a laboratory scale and full scale implementation of nanotechnology by the mining industry is not expected yet in the next decade [12].
However, as water from mines contains potentially valuable minerals, the use of magnetic nanoparticles combined with recovery and regeneration is especially appealing. Magnetic nanoparticles for recovery of, e.g. gold from water solutions has been demonstrated at the laboratory scale.

Another topical object for nanoparticle-based solutions is the removal of arsenic contamination. Arsenic occurs at varying concentrations in the earth's crust, from which it is mobilised by various biological and anthropogenic activities into groundwater and contaminates drinking water sources. Arsenic contamination of water is a global problem: it affects wells in countries with poor water management systems, is a common pollutant in mining wastewaters and bears high health risks. Arsenic incidents with severe health effects have been noted at least in Northern Chile, Mexico and Argentina. According to Larkins et al. [13] affordable arsenic removal can be done by using synthetic clay. Also Zinc oxide nanoparticles could help remove arsenic using a point-of-source purification device. Approaches based on trapping arsenic contaminants on magnetic nanoparticles have also been developed [14].

Water Monitoring

Within the category of sensing and detection, of particular interest is the development of enhanced sensors to detect biological and chemical contaminants present at very low concentrations in water. Nanotechnology has the potential to facilitate the development of continuous monitoring devices capable of delivering real-time measurements at low cost and with improved specificity [15]. The high surface to volume ratio of nanoparticles enables surface chemical and physical phenomena that are exploited by new sensor devices. For example, sensitivity can increase due to increased conduction, detection limits can be lower, very small quantities of samples can be analysed, direct detection is possible without using labels, and some reagents can be eliminated [15, 16].

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The beneficial characteristics of nanomaterials, such as enhanced reactivity, surface area and sequestration characteristics, form the basis of development work relating to highly sensitive water sensors. Examples of developing work include a gold nanocluster-based fluorescent sensor for highly sensitive and selective detection of cyanide in aqueous solution [17]. This involved the development of stabilized gold nanoclusters consisting of several tens of atoms, making them smaller than 1 nanometre in size, with a high affinity towards cyanide.
Moreover, semiconductor quantum dots (QDs), which are nanocrystals of inorganic semiconductors with diameters of 2–8 nm, have been used to develop optical sensors based on fluorescence measurements. This type of sensor could be used for environmental purposes for on-site identification of pathogens (like cholera toxin) in water [15].

Summary and current challenges

Nanotechnology-derived materials such as nanoadsorbents, catalytic material, nanostructured and reactive membranes, as well as bioactive nanoparticles have been applied to water treatment. These materials are of interest due to their large surface area, efficiency in removing contaminants even at low concentrations, enhanced affinity for specific contaminants, catalytic potential, and high reactivity. Table 2 below provides a list of applications demonstrating the general potential of nanomaterials in water technologies.

To become a reliable water treatment technology, a few challenges need to be met. So far, the environmental impact and toxicity of nanomaterials are poorly understood; therefore, the key challenge may be to gain regulatory and public acceptance for using nanomaterials in water purification. Other important issues include integrating nanomaterials in existing water purification systems

Table 2. Applications demonstrating the general potential of nanomaterials in water technologies.

Application	Current technologies	Current Challenges	Enabled by nanomaterials
Drinking water production Desalination	Membrane filtration (reverse osmosis	• High energy consumption implies high operational costs • Membrane fouling leading to high energy consumption and lower throughput because of increased need for membrane cleaning and backflushing	• Incorporation of nanoparticles can give the membrane material antifouling mechanisms • Lower energy consumption
Drinking water Disinfection	Chlorination Advanced oxidation	• Efficiency • Chemical consumption • Generation of toxic by-products such as organic chlorides • Resistant microbes, viruses	• Catalytic breakdown • No by-products • Degradation of viruses and microbes through various pathways
Drinking water Pollutant removal (heavy metals, arsenic pesticides etc.)	Precipitation through addition of chemicals Filtration	• Efficiency towards low concentration, • Generation of toxic by-products • Resistant microbes, viruses	• Catalytic breakdown, • No harmful by-products • Degradation of viruses and microbes
Wastewater treatment	Chemical flocculation, biological degradation	• Long residential time • Inadequate removal of certain micropollutants • No possibility for recovery	• Engineered nanoparticles can show very high selectivity towards targeted pollutants • Recovery /valorisation
Irrigation	Little control and management, overuse, leakages	• Controlled water delivery according to need, price of sensor networks	• Monitoring for precision use of irrigation • Wireless new affordable sensors • Soil amendment

and guaranteeing the availability of nanomaterials at scale, and at economically feasible prices. While the cost of different nanomaterial is decreasing, for example Brame et al. [18] reported that zero valent iron nanoparticles and TiO_2 can be produced at \$0.14/g and \$0.18/g respectively, some remain high, e.g. carbon nanotubes can be in the range of \$ 300/g [19]. However, more important than the cost of nanomaterials per se is the cost normalized to the volume of water treated, a factor that currently is widely unknown.

In the context of treatment and remediation, nanotechnology has the potential to improve both water quality and quantity in the long run through the use of, for example, advanced membranes enabling water reuse or desalination.

The use of nanofibres and composite nanostructured membranes can help degrade a wide range of organic and inorganic contaminants in real field applications. However, most work is still taking place in research laboratories and there are only few commercial applications on the market. A better understanding of the formation of nanocomposite membranes will certainly be a step towards improving their performance. The deposition pattern of nanoparticles within the membrane matrices, and changes in the structure and properties of both nanomaterials and host matrices are among the priority concerns for field applications for water/wastewater treatment.

With regards to potabilisation (drinking water production), the practical application of nanoparticles can be limited by unknown side-effects caused by their release into the environment. A careful evaluation of the physical and chemical stability of immobilized particles in aqueous media (natural or effluents) will be necessary for its judicious use. Environmental and health risks and unknown factors related to the use of nanomaterials in water treatment have also hampered water technology companies' interest in actively incorporating nanomaterials in their R&D and business lines.

Advances in nanotechnology for water in Latin America

Research and development activities focusing on nanotechnologies for water were gathered through bibliometric studies [20]. Those authors provide a list of leading experts, groups, institutions and main international collaborations with regards to expertise observed in three main water application categories: water desalination, contaminated water remediation and water potabilization. A summary of the main findings of the study of Invernizzi et al [20] is provided in the following paragraphs.

Overall, this research area is very new in LA countries. On the topic of water potabilization the first publications in the region appeared during the 1990s, and on the topic of water remediation, the first articles were published in the following decade (2000s). Of the three main water application categories, contaminated water remediation and water potabilization have almost equal output of publications (257 and 227 counts respectively as seen in table 3), whereas water desalination is the least researched of all.

Brazil and Brazilian institutions have the most outstanding output, followed by Mexico and Argentina. Taking a closer look at the production of some of the authors listed in the bibliometric map [20], one can conclude that the articles also described work on nanosensor development with applications in the water sector.

Interviews with researchers, although not having covered all the spectrum of work done in the field in Latin America, revealed that research and development nanoscience and nanotechnologies related to water deals with development of nanodevices for online sensing of metals and borate in water (Chile, Uruguay) and development of nanoparticles for water remediation based on sorption (Chile, Argentina), as well as catalytic degradation of nitrogen compounds, organic pollutants and reduction of mercorous chloride (Argentina).

Table 3. Publications output by technology, country and most productive institutions of LA in the field of nanotechnologies for water

Publications by technology	Publications by country	Publications by institutions
Contaminated water remediation (257) Water potabilization (227) Water desalination (3)	Brazil (360) Mexico (136) Argentina (90) Chile (56)	Brazil: USP (82), UNESP (51), UNICAMP (49), UFSC (28), UFRGS (27), UFRJ (21) Mexico: UNAM (45) Argentina: CONICET (27), UBA (18) Chile: Universidad de Concepción Chile (23)

Source: Based on Invernizzi et al [20]

Interviewed researchers mentioned clear connections between their work and the main social challenges. Their role does not only relate to technological solutions for improving the availability of safe, clean water and reducing environmental pollution. Developing solutions that utilizes national resources (foremost minerals) and increases their value, and teaching and advising young students and researchers in this thematic area were also mentioned as important factors for the overall development of the country. To note is that much ongoing research in nanoscience in LA relates to the generation and characterization (including stability in real environments) of nanomaterials for general applications, including environmental solutions. Although this work ultimately will serve the development of water solutions, the work as such is not specifically focused on a certain function.

As a specific contribution to the main social challenges for water, the removal of arsenic for potabilisation was mentioned. Arsenic contamination affects people in mining areas (e.g. in Chile, Mexico) and in areas with naturally high levels of arsenic in groundwater (e.g. Argentina). This challenge was seen as important for several LA countries.

Focus group type interviews revealed that the high cost of the nanomaterials is considered a barrier to the application of nano-based solutions for societal challenges. Further investigation for lower cost solutions is needed. When moving from basic research towards applications of nanotechnologies, these should be aligned closely to solve concrete problems in Latin America and prove their effectiveness through real socio-economic impact. Demonstration projects to show the applicability of new innovations are crucial to enhance the deployment of new inventions. These demonstrations should be installed in nationally relevant environments such as drinking water production sites and mining water remediation.

Applied research with local relevance

would involve, above all, potabilisation of water. For example, Mexico is today the largest consumer of bottled water in the world and families sometimes spend as much as 10% of their incomes on water. This is double what the Inter-American Development Bank estimates they should be spending. Further demonstration cases with potential impact are solutions for remediation and reuse of industrial (mining, food, chemical) process water.

A detailed qualitative analysis and collection of contact data was conducted for those countries that were identified as remarkably productive by the bibliometric study [20]. A summary of results follows with the disclaimer that, due to the different amount and quality of information available, the information between countries is not easily comparable. So, briefly, we summarize the findings by country interms of research groups and focus in table 4.

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Recomendations and roadmap

The following recommendations addressed the thematic of nanotechnologies and focus on specific solutions that could be produced for solving some of the societal challenges related to water. Most of the recommendations were gathered by means of individual or group interviews with stakeholders, mainly researchers, who attended NMP-DeLA's workshops; or responses from community of interest members to the questionnaire that was made available on the project's website. The recommendations are related to research, policy and funding, and industry involvement and investment in order to address identified problems, and to improve the industrial competitiveness of the water sector in LA, as an indirect result.

• **Building up a network of experts on water technology and nanospecialists,** by organising conferences or seminars focused on nanotechnologies applied to water. Latin American researchers could be linked to European networks, including experts from the United States of America, in those conditions were collaborations are already in place.

• **Jointly addressing problems that are common to member states of the region**. As an example, Mexico, Argentina and Chile's problems related to arsenic contamination.

• **Involving affected industry and society in the search for solutions.** Applied research should include the mining companies and local authorities with contaminated water problems. Social organizations should also be engaged in order to raise people´s awareness of water contamination.

• **Applications of nanotechnology in water treatment should be developed following safety by design principles.** End users should be involved from the beginning to make sure that solutions are useful to them.

• **Building up involvement of African, Latin American and European experts together to achieve a critical mass.** The nanotechnology community

Table 4. Focus of research on nanotechnologies for water in Latin American countries

Country	Focus of research in the country
Brazil	Nanotechnology for desalination, potabilization, environmental remediation and sensors/monitoring.
Mexico	Nanotechnology for water, remediation.
Argentina	Nanotechnology for remediation of contaminated water
Chile	Synthetic nanoparticles for removing arsenic, for perchlorate remediation in soil and cleaning water from heavy metals; synthesis of new materials for water decontamination; and polymer-clay nanocomposites for oxyanions removal
Colombia	Environmental remediation of water nanomaterials and sensors for water treatment and energy production
Uruguay	Nanotechnology for water

Source: Based on Invernizzi et al. [20]

Table 5. Roadmap recommendations and timeframe for implementation up to 2030

Topic	Short term (by 2020)	Medium term (2020-2025)	Long term (2025-2030)
Research	• Start of activities for improving the research infrastructure for conducting applied research in nanotechnology addressing water problems • Creating a network and a system for common utilization of laboratory equipment • Creation of a Latin America–European community for nanotechnology research • Detailed mapping of needs to improve the water situation in LA countries, as base for matching research to societal and industrial needs	• Establishment of a Latin American Association for Nanotechnology for environmental solutions • Establishment of first private-public partnership between Latin American research organisations and innovative indutry • Benchmarking of national initiative on developing solutions for improved availability of water and water availability nanowater in public waste management	• Support for high technology readiness level of development
Funding	• National, regional and bilateral funding (European-Latin American)	• Use Bill and Melissa Gates foundation and World Bank funds to finance.	• Use of World Bank funds
Infrastructure	• Intensified and systemic collaborative use of research infreastructure involving European and Latin American research organisations	• Construction of pilot scale applications with verified long term viability in new environemnts (e.g. desalination) • Affordable commercial solutions available on small scale	• Establishment of large demonstration plants in the water intensive industry and/ or public water utilities
Technology Transfer	• Creation by the European Water Technology Platform of an action group for actions and collaboration in Latin American countries. • The European Innovation Partnership for Water opens up to participation of Latin American countries	• Good practices of technology transfer are transferred from more mature water technology solutions in Latin America to the nano-water sector	• Establishment of public-private partnerships for deployment and development of solutions (potabilisation, water recycling and reuse, monitoring networks, etc.)
Policy making	• Inclusion of nanotechnologies, and focus on for water, in the working group for biregional European-Latin American policy dialogue	• Implementation of recommendations on water availability and safety issues by national governments	• Development strategy for leadership in securing safe drinking water
Cooperation	• Inclusion of nanotechnology as a priority topic in the EU-LA Joint Initiative for Research and Innovation (JIRI)	• Latin American institutions engage with developing solutions for water with regional (IDB, WHO, FAO, Brazil-Argentina Nanotechnology Institute) and international (e.g. WHO, WB, WssTP) actors	• Establishment cooperation between the water intensive industry and research organisations for deployment of nano-based solutions for water recycling and pollutant removal

could organise conferences on water treatment by solar energy, combining both energy and water in a nanotechnology framework, and bringing scientists together to solve common problems. Engagement with the International Water Association (IWA) could be useful in this regard, as the Association is doing work in Africa and bringing conferences to Africa.

• **Apply nanotechnology in remediation of mining water effluents, especially membranes.** The main problem is that there are few nanotechnologies for water applications at industrial scale, most are at lab-scale. These are still expensive and will take a long time to reach market. Another issue is solving the footprint of post-treatment and regeneration of used nanomaterials. For example the use of acetone to remove pollutant from nanocatalysts and how this wastewater is finally disposed of.

• **Opportunities for cooperation between Europe and LA** in scaling-up lab research and development on membranes and catalysts for arsenic, microbes etc.

• **To scale up developments from lab scale or pilot scale to industrial scale in the long term**. In general, nanotechnology for water and wastewater treatment is at the lab scale and it has not been deployed in real life. Its promising breakthroughs are foreseen in the coming years, so scaling up promising university developments for water purification to pilot or full scale in the long term is the aim. Furthermore, it is important to keep in mind the environmental fate, stability and toxicity.

• **Point of use technologies in developing countries, to be installed, for example, in houses at point-of-use (e.g. sinks, or drinking water).** Another potential application is, for example, the use of palladium as photocatalyst to be used for the catalytic reduction of nitrates. Point-of-use technologies will also be of interest to water desalination were technological innovation could enable small scale desalination.

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In general, socio-economic factors such as poverty, poor living conditions and lack of access to clean water, pose serious regional obstacles in LA. Increased scarcity of (clean) water, and extreme weather events, induced by climate change as well as industrial pollution, will call for improved and affordable technological solutions. The opportunities for nanotechnologies for water in these settings could have a major positive contribution.

Nanotechnologies applied to water potabilisation, (industrial) waste water treatment and monitoring, will need to be developed from lab-scale demonstrations to regionally relevant applications, and progress to market is expected towards 2030. The main advantages of nanotechnology-derived solutions include more effective and cost-efficient solutions with less unwanted formation of hazardous by-products and waste. Below in table 5 we list recommendations followed by a suggested timeframe for their implementation.

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