NANOTECHNOLOGY IN WATER TREATMENT

10% of global population does not have access to improved drinking water sources

49% of global grain production will be at risk due to water stress by 2050

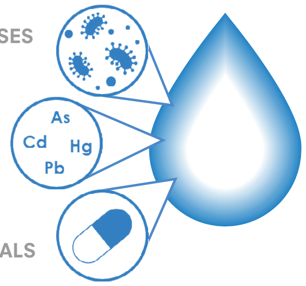
Up to **90%** of wastewater in developing countries flows untreated into water bodies

1.5 Billion people world-wide suffer from water-related diseases each year [12]

BACTERIA & VIRUSES

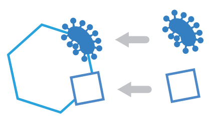
HEAVY METALS

PHARMACEUTICALS



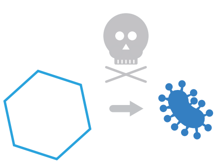
ADSORBENTS

attract contaminants in the water, which become attached to its surface.



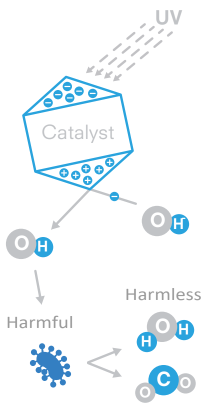
DISINFECTANTS

directly kill biological contaminants through slight toxicity, for instance by destroying the cell walls of bacteria.



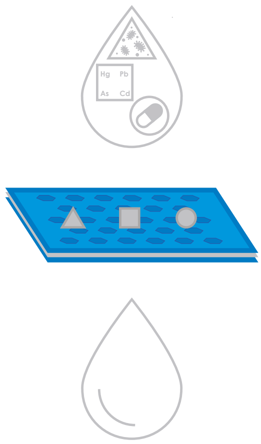
PHOTOCATALYSTS

when activated by UV light, break down pollutants into non-toxic by-products.



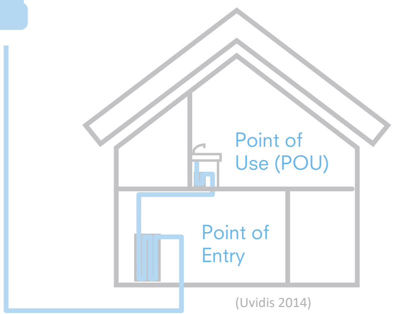
MEMBRANES

act as a selective barrier within water, hindering solids bigger than their pores to pass through them.



87% of the population in developing regions uses an improved source of drinking-water (UN water 2014)

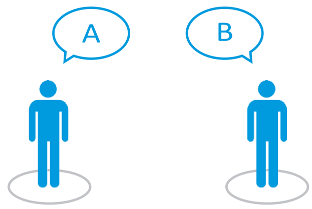
80% of the people who do not use an improved source of drinking-water live in rural areas (UN water 2014)



(Uvidis 2014)

CHALLENGES

Public inclusion



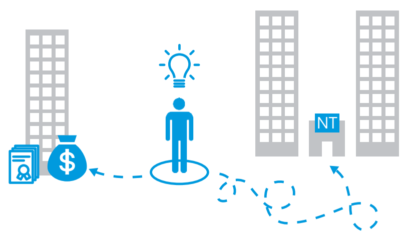
FACT: No evidence was found that a shift towards the inclusion of possible end-users of developing countries will take place in the near future.

Risks

Uncertainty surrounding risks because of a lack of data

FACT: Whether a NP is hazardous or not depends on: its size, shape, nature, surface chemistry and charge, reactivity, agglomeration and aggregation properties, mobility, stability, medium and storage time and the environmental situation.

Economic inclusion



Multinational

Local Start-up

FACT: In Tanzania, a local entrepreneur was able to commercialize a low-cost and customized nanofilter for local household and communal use, after receiving training and a grant on business development [68].

NANOTECHNOLOGY IN WATER TREATMENT

KEY MESSAGES

- **Nanotechnology (NT) can cost-effectively treat contaminants in water that are untreatable by conventional[a] methods.**
- **Adsorbents, disinfectants, catalysts and membranes have the potential to become widely applied technologies in developing countries if the needs of these countries are reflected in the R&D and investment strategies.**
- **Challenges formed by risk uncertainty, economic inclusion and public inclusion obstruct the large-scale application of NT and an equal distribution of the related benefits.**

INTRODUCTION

According to the World Economic Forum (WEF), a decline in the available quantity and quality of fresh water is the main global risk that the world society will face the coming decade [1]. It is expected that by 2025, 1.8 billion people will live in countries or regions with absolute water scarcity [2]. The dependent relationship between water quality and water availability is thus a topic that needs attention. This is especially the case for developing countries where fresh water sources are often contaminated by bacteria, viruses and heavy metals, due to inadequate sanitation infrastructures, mining activities and the disposal of untreated industrial waste into water bodies [2],[3]. Since conventional methods are reaching their limits to deal with these problems and adequate water infrastructures are often lacking in developing countries, a new solution is needed [2],[4],[5].

1.5 Billion people world-wide suffer from water related diseases each year

The realization that NT could provide the answer has already been there since the beginning of the 2000s, when the technology was formulated as a solution to the targets set for clean water in the Millennium Development Goals [6]. However, the large scale application of NT in water treatment in both developed and developing countries is still hampered by multiple issues, such as the uncertainty regarding the risks of nanomaterials (NMs), the difference in involvement in the R&D of NT between developed and developing countries and global disagreement about regulation standards on the usage of NMs [7]-[10]. Nevertheless, the potential for NT to address global water concerns is still strong [7],[11].

Bacteria, viruses and heavy metals, which cause 1.5 billion people world-wide to suffer from water-related diseases each year, can be treated more efficiently and cost-effectively by NT (SDG 3: Good Health and Well-Being) [7],[12],[13]. In a similar manner, the treatment of water by NT can improve the production of agricultural crops, by preventing salinization and contamination of agricultural soils (SDG 2: Zero Hunger) [12],[14]. Finally, NT has the potential to create a new domestic industry in developing countries, which can create new jobs, new knowledge and be a standard for creating new water infrastructures (SDG 9: Industry, Innovation and Infrastructure) [12],[15],[16].

Within this policy brief **nanotechnologies** are defined as devices and systems with a size of 1 to 100 nanometres (1 billionth of a metre) in at least one dimension, which take advantage of the unique properties of particles at this scale [17],[18]. However, one should be aware that there is an absence of an internationally recognized working definition of NT [19].

CURRENT STATUS

Although some commercialization of NT water applications has taken place, the majority is still in the R&D phase and upscaling applications is one of the major challenges [20]-[22]. R&D mostly takes place in the United States, Europe, China, India and to a lesser extent in Brazil and South Africa [14],[22],[23]. Investments are made by both public and private sector, but unfortunately no detailed numbers are available [9],[24],[25]. With regards to governance, NMs are mostly administered through the general regulation on chemical production and distribution and through existing environmental and water regulations [7],[26]. At present, amendments are being made to these regulations to regulate NMs specifically [7],[27]. Yet, there is an international debate on whether this is sufficient or more specific regulations on NMs should be implemented [7].

BENEFITS

Compared to other sectors, NT in water is perceived favourably due to its societal importance and perceived necessity [28]. NMs remove contaminants, bacteria and viruses more efficiently due to their increased specific surface area[b], reactivity and dissolution capacity and thus contribute to the improvement of current disinfection[c], purification and desalination techniques [7],[29],[30]. The application of NTs within water treatment leads to reduced use of chemicals compared to conventional disinfection techniques (e.g. chlorination and ozonation) whose by-products can also have negative impacts on human health and the environment [7],[30]. Because of the low concentrations of emerging pollutants (micropollutants, pharmaceuticals, personal care products and hormones) present in wastewater, NT solutions for more efficient treatment methods are needed [31],[32]. The same applies to industrial wastewater which is often contaminated with heavy metals (e.g. chromium, mercury, lead and cadmium) [30].

Case Study: 'Drinkwell' and the first filter that can remove arsenic and fluoride from groundwater
NT applied: Polymeric ion exchangers[d] doped with zirconium oxide NPs (adsorbents) which can within a filtration column be attached to wells [35].
Contaminant removal: arsenic, fluoride, phosphate and lead.
Target group: people who live in affected areas in India, Laos, Cambodia, Bangladesh and Kenya.
Technical benefits: robust material, energy-efficient, can be re-used and regenerated for years, applicable in local context.
Socio-economic benefits: In comparison to the required installation for a similar water purification result, the NPs are a cost-efficient treatment technology. The NPs are used in small decentralized treatment systems which don't require large investments, management structures and costly maintenance [34]. The organization 'Drinkwell' thus empowers villagers to run their own plant in a sustainable manner and allows them to make small profits [35]. A micro-franchise model is used which foresees that the plant is owned by the village committee and maintained by one or two compensated caretakers [36]. Apart from this, additional jobs are created since the NPs are produced in plants in India [36],[37]. Besides, a waste management process was introduced in order to prevent that arsenic is returned back into soils [37]. The risk emanating from remaining NPs in treated water is conceived of secondary importance when considering the number of early deaths caused by arsenic-contaminated water.

In affluent countries, NT upgrades to existing infrastructures can be implemented in a cost-effective manner [4]. Once implemented, NTs increase the performance of many treatment systems. In general, NT solutions are considered as cost-effective since in many devices or systems insignificant amounts of NPs are used (see Table 2) [32]. Additionally, NTs are often more energy-efficient since they reduce the energy needed as for example in the case of membranes. Finding numbers on the cost-effectiveness of current NTs is difficult because conventional filters often address different contaminants, show diverse operational requirements and life spans. Nevertheless, an increase in production capacities generally contributes to the cost-effectiveness of nanoparticles (NPs) (see Table 2) [32]. Developing countries could strongly benefit from recent developments since NTs do not necessarily rely on existing water infrastructures, require less energy input and can be delivered in smaller quantities [4],[30],[33]. NTs within water treatment offer countries, which lack water infrastructure, leapfrogging opportunities (e.g. foregoing the installation of large centralized treatment systems) and the opportunity to focus on more flexible applications [20],[24],[34]. Decentralized NT-based treatment systems or POU[e] devices will, particularly in developing countries, alleviate life-threatening water quality problems and contribute to improved health and well-being [4].

POTENTIAL

In this section the most promising trends for four NTs in water treatment are highlighted: adsorption, disinfection, photocatalysis and membranes. For all four, translating promising results in the lab to the field remains the biggest challenge [10],[38].

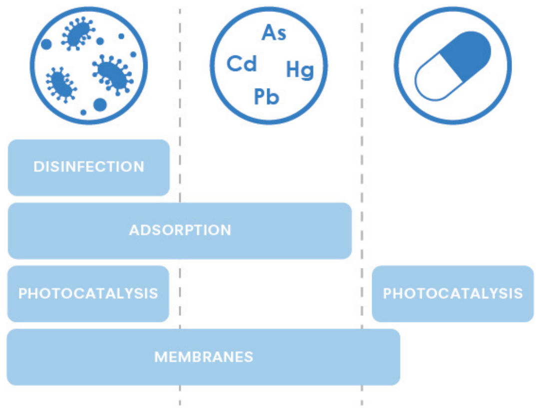


Table 1: Addressed pollutants (pathogens and heavy metals, pharmaceuticals) per nanotechnological water application

Adsorption

Adsorption[f] is an established technology that can be improved using NPs. It can address persistent toxic metals such as arsenic that are less easily treated using conventional technologies [38].
Adsorbents attract contaminants in the water, which become attached to their surface. Afterwards, they are removed and disposed of by, for instance, using nanofiltration methods [10],[39].
Iron-oxide NPs are relatively cheap and well-tested adsorbents to clean groundwater from heavy metals [38]. In addition, nanocellulose is a promising future adsorbent for developing countries due to its biodegradability and potential cost-effectiveness, but it still requires substantial R&D [24].

Disinfection

Disinfection[g] using NPs can remove bacteria and viruses without using harmful chemicals, making them superior to existing disinfection techniques [5],[7].
NP disinfectants kill biological contaminants through slight toxicity, for instance by destroying the cell walls of bacteria [40].
Silver NPs are a suitable disinfectant because they are non-toxic even under limited exposure [41]. Also, their production process is simple, cheap, and the particles last long (up to 5 years) [5]. As a result, the technology is applied in developing countries, such as South Africa and India [42],[43].

Photocatalysis

Photocatalysis is a relatively new NT for the treatment of water. Nano-catalysts are highly effective for treating dangerous pathogens such as E.coli, and can remove compounds such as pharmaceuticals, which are out of reach of conventional methods [10]. Although photocatalysis can theoretically remove toxic metals like mercury, chromium and arsenic, it remains difficult to do this in the field [5],[44],[45]. Overall, photocatalysis is an effective, but highly specific method [20].

Photocatalysis uses nano-scale particles that, when activated by UV light, break down pollutants such as viruses, bacteria and pesticides into non-toxic by-products. After use, the NPs remain unchanged and can therefore be collected and re-used [46].

The most common and cost-effective method for UV photo-catalysis involves the use of Titanium Dioxide (TiO_2) NPs [10]. Three major advantages of TiO_2 photo-catalysis are the relatively modest technical installation, minimal operating experience required, and low implementation cost. This makes the technology especially useful in rural areas. Photocatalytic systems have been validated in Trinidad and Tobago and Swaziland, where a pilot installation successfully removed 99.9% of viruses and bacteria in only 60 seconds of treatment time [47],[48].

Membranes

Membranes act as a selective barrier within water, hindering solids bigger than their pores to pass through them [30]. They are categorized according to their increasing filtration capacities with decreasing pore sizes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membranes [30]. The smaller the pore sizes, the higher the pressure and subsequently the energy required to push the water through the membrane [49]. Therefore, research focuses on finding ways to improve cleaning ability without reducing permeability[h] or ease of fabrication [4],[7].

For potable water purification, multifunctional NF and UF membranes hold the greatest potential since their permeability is increased due to a better cleaning process resulting from the incorporation of NPs [4],[20],[50].

Multifunctional membranes[i] incorporate NPs such as adsorbents and catalysts [20],[22]. These nanofillers (e.g. nanosilver, carbon nanotubes, titanium dioxide, polymer coated NPs) increase the membrane's resistance to fouling[k] and its selectivity [4],[22],[50],[51].

The properties of multifunctional membranes depend on the specific NPs incorporated. Nano-enhanced membranes require a stronger focus on long-term risk assessment since NPs might leach [50].

Due to the high energy requirements and the treatment plant's size necessary to operate NF and RO membranes, less developed countries should rather opt for functionalized UF membranes or even low pressure driven MF membranes for decentralized and POU systems [20],[52].

Increasing emphasis is put on biologically inspired or bio-based membranes such as aquaporins or cellulose nanomaterials (CNs) [24],[53],[54]. Both enhance the membrane's performance immensely, particularly its selectivity and permeability [52],[55]. CNs constitute a biodegradable, cheap and sustainable material whose strength contributes to the membrane's stability [54]. The rapidly increasing number of CN-related patents highlights its potential [54].

Aquaporins are proteins which are able to remove most ions by forming water channels when embedded in membranes [7]. Current limitations to their large commercial application are their unavailability in large quantities, cost-intensiveness, and complex manufacturing process [51],[52].

Since the production of CNs and aquaporins is not efficient yet, R&D for a more sustainable manufacturing process is required [24],[52],[54]. CNs could be generated out of every kind of locally available biomass which also requires further research [22],[24].

	Cost until first replacement	Replacement Cost	Cost for 3000 litres
Gongali (nano)	$0,163/litre	$0,006/litre	$143,60
AMRIT (nano)	$0,011/litre	$0,0006/litre	$17,40
Aquasana (non-nano)	$0,058/litre	$0,035/litre	$144,33
GX1S50R (non-nano)	$0,028/litre	$0,026/litre	$83,70
BRITA F&E (non-nano)	$0,224/litre	$0,061/litre	$199,30

Table 2: Price estimate comparison of water filters [56]-[62]

CHALLENGES

Risks

Uncertainty: Since human beings (by penetration of the skin or ingestion) and ecosystems are sensitive to the exposure of NPs in water, a concern about the toxicity of NPs is often expressed [8],[21]. Although much data has been gathered over the years, a significant gap of knowledge on the intrinsic hazardous properties of NPs and their behaviour in different environments still exists [7],[27],[63],[64]. This gap results from the indeterminate behaviour of NPs and the lack of general standards to conduct risk assessment research [7],[8],[65]. Due to this, results from research are incomparable and conclusions on actual risks remain uncertain [7],[8],[65]. Consequently, main stakeholders in the water treatment industry in developed countries, like water service companies, have been reluctant to use NT, which has impeded its large-scale application [10], [20],[27],[53].

Management & Perception: The dynamic and rapid setting in which R&D takes place, together with the lack of general standards on risk assessment has caused regulation on NPs to lag behind [66],[67]. Furthermore, due to differences in political interests, the governance of NPs mainly takes place on national or regional level, whereas the transboundary nature of NPs requires international cooperation [67]. While in the EU and the US risk assessment is an essential part of the commercialization strategy, countries such as India and Brazil often neglect risk assessments as it is believed to hamper their competitive position on the market [25],[63],[68]. The dilemma in place is to find a balance between promoting innovation, so that the socio-economic benefits of NT in water treatment can be realized, while simultaneously controlling the risks to such an extent that it prevents humans and ecosystems from being harmed [20].

Addressing Risks: Risks of NTs in water treatment can be mitigated by immobilization, collection and re-use of NPs through membranes or magnetic particles [5],[10]. Creating NMs based on biological materials such as cellulose can also reduce risks, because NMs become more bioavailable and may be broken down before they can cause significant harm [48],[53],[63]. Furthermore, current efforts are being made to develop new analytical methods to assess the effects and the behaviour of NPs more extensively, especially in the EU [27],[36].

Economic Inclusion

One of the opportunities of NT in water applications is that it can provide the base for a new industry in developing countries, once applications developed in the laboratory are translated into commercial products [15],[16]. However, at the moment it is challenging for researchers and entrepreneurs from developing countries to realize this commercialization path [16],[66]. First, the access to financial resources is limited, as funding for NT water applications is not a priority for governments [65],[69]. When small local start-ups do get the chance to emerge and enter the global market, they are often outcompeted by large multinationals [5],[25]. Second, researchers involved in NT in water applications often lack the skills to commercialize these applications. Intellectual property is already strongly defined in Western countries, but a 'patenting culture' is not self-evident in most developing countries [16],[25],[70]. Consequently, developing countries cannot gain a substantial share in the global market and young, talented researchers move to developed countries for greater economic opportunities [25],[70],[71]. This "brain-drain" further reinforces the weak position of developing countries in NT development and commercialization, wherefore opportunities to reap the socio-economic benefits from NT are missed [25],[71].

Public Inclusion

As for any new technology, public perception plays a crucial role in the acceptance and adoption of the technology by end-users [36],[72]. Therefore, the commercialization of NT water applications developed for end-users in developing countries is dependent on local opinions about the relevance of such an application [68],[73]. Yet, the inclusion of this target group during the R&D phase of the application is often lacking and the application is developed according to what researchers believe to be the solution rather than on what possible end-users in developing countries think is needed [36],[68],[71],[74]. Due to this approach, there is a risk that the implementation of the application will in the end be hampered and valuable resources are wasted [68],[73],[75]. The challenge in this respect is to overcome the financial, social and physical barriers between the location where the R&D takes place and there where the final product is supposed to be implemented.

POLICY RECOMMENDATIONS

INDUSTRIAL DEVELOPMENT

- Global investments in NT should focus on low-tech applications for decentralized treatment plants and POU devices which are affordable for local communities in developing countries.
- Financial support for local start-ups in developing countries working with NTs in water treatment should be encouraged until they are able to compete with more established companies.
- Institutional investors should foster local entrepreneurship, by making funds available for capacity building on how to commercialize new applications.

R&D

- R&D should focus more on bio-based NMs (e.g. aquaporins, cellulose) in order to enable sustainable applications.
- Future R&D should include cost-benefit analyses, and this information should be systematized to enable comparison between NTs.

RISK ASSESSMENT

- Global standards for the assessment of risks and the harmonization of existing risk assessment tools should be realized as quickly as possible.
- Future risk assessment should focus on the development of analytical methods that address the long-term effects of NPs on human health and environment.

STAKEHOLDER ENGAGEMENT

- Social dialogue between researchers of NT water applications and targeted end-users should be facilitated on a global level in a way that enables two-way responsiveness.
- Liaisons between relevant stakeholders from developing and developed countries, especially research institutes and universities, should be established to stimulate transfer of knowledge.

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Juliana Kessler, and Fenna Wielenga

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The views expressed in this policy brief do not necessarily reflect those of Wageningen University & Research, nor the experts consulted.
Experts speak on their own behalf and their views do not necessarily reflect the views of their institutions.

Footnotes

a. Traditional methods (e.g. coagulation, sedimentation, sand filtration and activated carbon) and advanced methods (e.g. non-nano filtration and advanced oxidation).

b. Higher surface area to volume ratio.

c. Process by which pathogens are removed from the water.

d. Harmful ions in the water are replaced (attached by adsorbents) with harmless ions.

e. Household-level treatment system.

f. Particle binds with a toxic compound to neutralize it.

g. Process that kills biological contaminants.

h. Quality of a membrane which allows particles to pass through it.

i. Surface functionalized membranes & mixed-matrix membranes.

j. Prevention of particle deposition on membrane.

k. To fix the position of NPs on a surface (e.g. on a membrane).

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