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Global arsenic dilemma and sustainability

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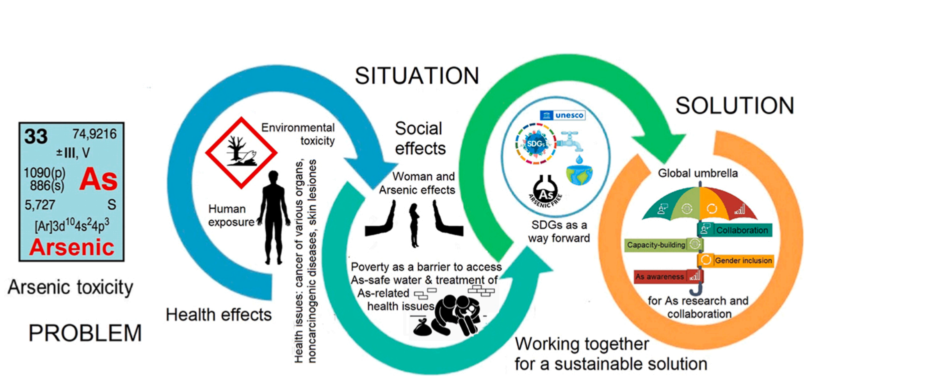
HIGHLIGHTS

- Contamination of As in rice and baby cereal via export/import is a global problem.
- Ensuring As-safe drinking water and food is still not considered as a human right.
- It is a key priority in UN's 2030 Sustainable Development Goals (SDGs) and UNESCO's global priorities.
- A global umbrella for sharing knowledge, experience and resources is an urgent need.
- This analysis and review lends a fresh perspective for a sustainable As mitigation by 2030.

GRAPHICAL ABSTRACT



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ABSTRACT

Arsenic (As) is one of the most prolific natural contaminants in water resources, and hence, it has been recognized as an emerging global problem. Arsenic exposure through food exports and imports, such as As-contaminated rice and cereal-based baby food, is a potential risk worldwide. However, ensuring As-safe drinking water and food for the globe is still not stated explicitly as a right neither in the United Nations' Universal Declaration of Human Rights and the 2030 Sustainable Development Goals (SDGs) nor the global UNESCO priorities. Despite these omissions, addressing As contamination is crucial to ensure and achieve many of the declared human rights, SDGs, and global UNESCO priorities. An international platform for sharing knowledge, experience, and resources through an integrated global network of scientists, professionals, and early career researchers on multidisciplinary aspects of As research can act as an umbrella covering the activities of UN,

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UNESCO, and other UN organizations. This can deal with the mitigation of As contamination, thus contributing to global economic development and human health. This article provides a perspective on the global As problem for sustainable As mitigation on a global scale by 2030.

1. Introduction

1.1. What is at stake?

Arsenic (As) found in almost all environmental matrices, is the most critical natural contaminant of global concern due to its highly toxic effects on different life forms, including humans (e.g., Ravenscroft et al., 2009; Kapaj et al., 2006; Shankar et al., 2014; Fatoki and Badmus, 2022). It ranks number one in the Agency for Toxic Substances and Disease Registry's Priority List of Hazardous Substances (ATSDR, 2020) of the USA. Humans may be exposed to As through food, water, and air and skin contact with soil or As-contaminated water (e.g., Fergusson, 1990; Gadgil, 1998; Howard, 2003; Ravenscroft et al., 2009; Chung et al., 2014). Geogenically released As is a long known global issue as As occurs naturally in the environment (e.g., Vithanage et al., 2017; Ceriotti and Guadagnini, 2021; Raju, 2022). Over 200 million people in at least 105 developing and industrialized countries are at potential risk of As poisoning, primarily due to ingestion of As-contaminated drinking water (e.g., Ravenscroft, 2007; Naujokas et al., 2013; Podgorski and Berg, 2020). People are exposed to a highly toxic inorganic form of As at elevated levels through drinking contaminated water, using contaminated water in food preparation and irrigation of food crops, eating contaminated food and smoking tobacco (WHO, 2004; Heikens, 2006; Huq et al., 2006; Ohno et al., 2007; George et al., 2014; Biswas et al., 2021). Although the latter is a well-known significant risk to the health of the smokers, little known is the fact that As is among the components of the tobacco smoke present at concentrations of toxicological concern (e.g., Talhout et al., 2011; Campbell et al., 2014). Long-term exposure to inorganic As, mainly through drinking water and food, can lead to chronic As poisoning, skin lesions, and skin cancer, the latter two being the most characteristic and visible effects (e.g., WHO, 2004; Yu et al., 2006; Hong et al., 2014).

1.2. Not just a Third World problem

Notably, new countries and regions from where the As contamination problem was not reported previously are added every year; consequently, the known number of affected people keeps increasing, demanding more stringent regulations (George et al., 2014; Signes-Pastor et al., 2017). Nevertheless, less than half of the world has a likelihood of less than 20% of encountering groundwater with less than 10 μg/L As (Fig. 1, modified after Podgorski and Berg, 2020), which could very well be due to complete lack or paucity of data and/or low concentrations of As in those aquifers.

It is also worth mentioning that poor people are at a greater risk of As poisoning for not being able to afford purified water (UNESCO-WWAP, 2003; UNDP, 2004; Argos et al., 2007; FAO, 2015). Therefore, developing countries have to be the main target for mitigation of the global As problem. In developed countries, As contamination of drinking water resources does exist. Still, it is not alarming, as the problem is solved by suitable water treatment technologies, although at a high cost. Nonetheless, the As problem is not entirely resolved in these countries; e.g., in the USA, where over 2 million people use drinking water from private wells with As concentrations exceeding the regulatory limit of 10 μg/L (George et al., 2006; Ayotte et al., 2017; Schreiber, 2021; Spaur et al., 2021; Zheng and Flanagan, 2017). Also, As present in rice is no longer a local issue limited only to the countries where rice is grown using As-contaminated irrigation water and soil (e.g., Abedin et al., 2002; Delowar et al., 2005; Dittmar et al., 2007, 2010; Potera, 2007; Rahman et al., 2008; Bhattacharya et al., 2009; Carbonell-Barrachina et al., 2009; Chou et al., 2014; Sandhi et al., 2017; Hassan et al., 2017; Upadhyay et al., 2020; Saha et al., 2022). It is now recognized as a global issue due to the worldwide trading of rice and rice products, viz., cereals, from these countries (Moore et al., 2010; Jackson et al., 2012; Ashmore et al., 2019). This is especially valid and concerning for baby food prepared from rice in many developed countries, e.g., Australia (Gu et al., 2020),

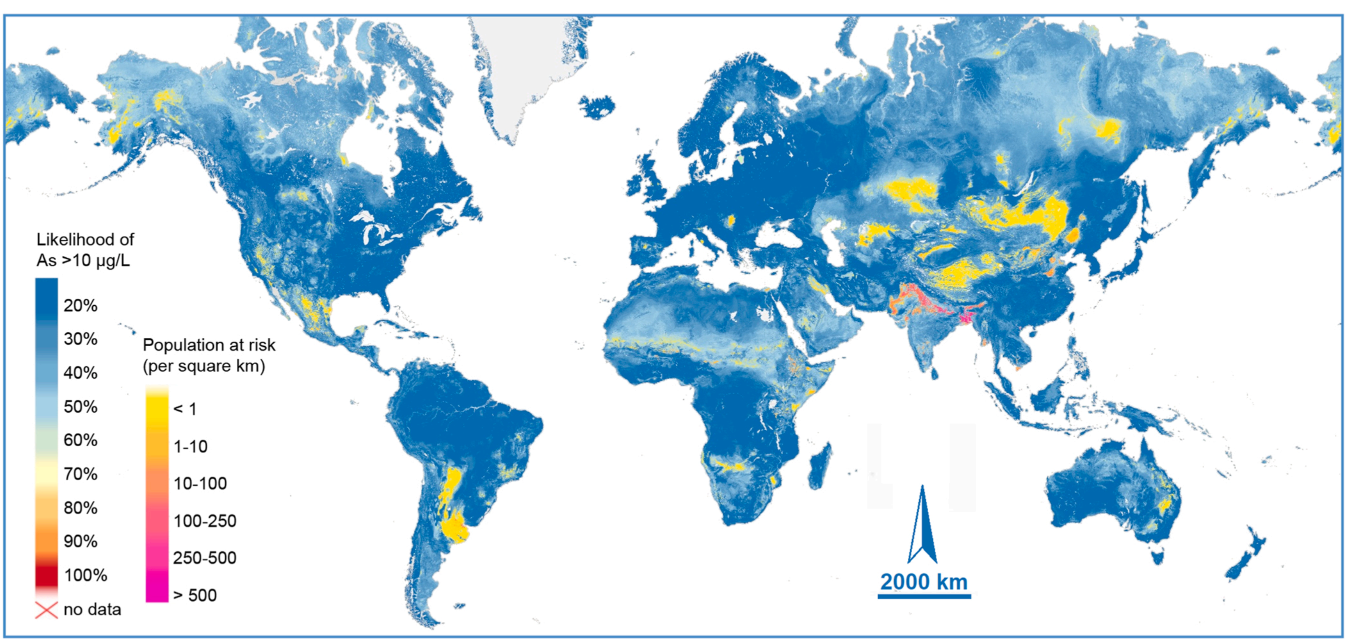

Fig. 1. Likelihood of encountering As contaminated (As >10 μg/L; WHO, 2004) groundwater, based on the predictive geostatistical model with the overlay of estimated population at risk from the same study (Podgorski and Berg, 2020).
Modified from Groundwater Assessment Platform (GAP) Map (https://www.gapmaps.org).

UK (Signes-Pastor et al., 2017), USA (US HoR, 2021). What aggravates this concern is that rice contains predominantly inorganic As (e.g., Meharg et al., 2008; Signes-Pastor et al., 2009; Rintala et al., 2014; Ashmore et al., 2019; Gu et al., 2020), which is much more toxic than organic As species dominant in most other plant species (e.g., Meharg and Hartley-Whitaker, 2002; Raab et al., 2007; Mishra et al., 2017; Abbas et al., 2018; Coelho et al., 2020; Wang et al., 2021).

1.3. Is the solution in sight?

Arsenic research on geological, geochemical, technical, environmental, biological, and social aspects and awareness of population and stakeholders are still inadequate. Integrated and holistic approaches are rare, and coordinated global strategies are generally absent or poorly understood. Overlooking (i) the impacts of chronic As exposure on humans through drinking water even at low concentrations (e.g., Yoshida et al., 2004; Naujokas et al., 2013; Kapaj et al., 2006; Sinha and Prasad, 2020; Wongsasuluk et al., 2021) and (ii) differing toxicity of As species (inorganic ones being the most toxic; e.g., Meharg and Hartley-Whitaker, 2002; Raab et al., 2007; Mishra et al., 2017; Abbas et al., 2018; Coelho et al., 2020; Wang et al., 2021) in food has led to some irrational, inadequate, and ineffective regulations. This has led to either too stringent (translating into unnecessary high costs of treatment) or too lenient (resulting in an increased exposure leading to health impacts with respective social and economic consequences) regulations. How the world has confronted the Covid-19 pandemic is a perfect analogy; precisely, the measures to prevent its spread have not been equally stringent and effective, depending on the socioeconomic realities of the countries. The latter has also been consequential in the way the affected population was treated, and mitigation (viz., vaccine) steps were taken in different parts of the world coupled with the local governments' available resources, policies, and priorities. Moreover, the regulations are based on As as the sole contaminant while setting the permissible limits for drinking water, not considering other sources (e.g., food; CONTAM, 2009) of As exposure or co-exposure to other natural or anthropogenic pollutants and vice versa; e.g., cadmium, fluoride, etc. (e.g., Alarcón-Herrera et al., 2013; Perera et al., 2016).

1.4. Need for a sustainable approach

A global umbrella for coordinated transdisciplinary and transsectorial capacity building and knowledge base is needed to address this problem holistically and sustainably. It should facilitate research, postgraduate and professional training, teaching, and solid global networking, to promote and channel cooperation and collaboration between participating universities and other stakeholders. Furthermore, the use of diverse information sources and integrated approaches for knowledge transfer through due recognition of intellectual property and rights will help in linking (i) the occurrence of geogenic As, (ii) contamination of groundwater and surface water, soil, plant, and air, (iii) their effects on the humans especially, and (iv) mitigation and remediation efforts.

Hernandez et al. (2019) presented a successful case of taking electrochemical arsenic remediation (ECAR) technology developed by the researchers at the University of California-Berkeley (UCB) and Lawrence Berkeley National Laboratory (LBNL) in 2006 to the West Bengal state of India for its commercialization. The collaboration of UCB and UCB with the Global Change Program of Jadavpur University (GCP-JU) and local private industry group, received financial support from the Indo-US Technology Forum (IUSSTF) from 2012 to 2017. This collaboration targeted several sustainable development goals (SDGs) while addressing the arsenic public health crisis's technical, socioeconomic, and political aspects. This case highlighted the significance of designing a technology contextually, bridging the knowledge divide, supporting local livelihoods, and complying with local regulations within a defined Critical Effort Zone period with financial support from an insightful funding source focused on maturing inventions and turning them into novel technologies for commercial scale-up. Moreover, it underscored the importance of building trust with the community through repetitive direct interactions and communication by the scientists, which was vital for bridging the technology-society gap at a critical stage of technology deployment in this case. Thus it filled a knowledge gap regarding successful case studies in which the arsenic remediation technology obtains social acceptance and sustains technical performance over time while operating with financial viability (Hernandez et al., 2019).

However, there is a general lack of such collaboration, especially globally. Consequently, desirable environmental and socioeconomic outcomes are insufficient and require a global network for collaboration between academia of the developed, developing, and underdeveloped countries in association with the development agencies. Moreover, addressing social norms and psychological aspects of the As-related issues are also fundamental, which have been rarely considered (e.g., APSU, 2006; Islam, 2014). This can be achieved through better cooperation and collaboration within local and international scientific communities and development agencies. In this context, awareness creation, knowledge exchange, and providing scientific information in everyday language for public communities through outreach programs will lead to positive outcomes of the joint efforts with improved support, better participation, and increased benefits for the social initiatives.

The global collaboration between academia and development agencies, along with the participation of local communities, will lead to immediate solutions to mitigate the problem with multiple technological perspectives and alleviate socioeconomic and environmental concerns. For example, domestic water collection and use have traditionally been women's responsibilities, particularly in lower-income As-endemic regions, particularly in South Asia. So the inclusion of women in planning and decision-making at the community level should be part of the strategies developed by the academia in association with the development agencies.

1.5. The way forward

In this paper, we analyze the situation of the global As problem-based on international development scenarios concerning (i) population growth, (ii) livelihood, and (iii) industrial activities and resulting increases in demands for freshwater, energy, food, raw materials (e.g., biomaterials, minerals). In particular, we consider respective forecasts, related needs, and perspectives to better integrate and align the global As problem in existing general inter-sectorial international programs of the United Nations (UN) and its organizing bodies, viz. United Nations Educational, Scientific and Cultural Organization (UNESCO).

Inter-sectorial and transdisciplinary global programs and treaties are excellent formal or informal links or platforms to integrate As-related topics. They crosscut all the fields related to humanity (e.g., science, economics, social, environmental, and educational issues), as envisaged in the 2030 Agenda for Sustainable Development of the United Nations (UN, 2015a; UN, 2020). Moreover, there are various programs of UNESCO with well-defined regionally-focused (Section 2.3.1) and thematically-focused (Section 2.3.2) priorities.

So far, these do not specifically include the topic of As. However, As is mentioned along with fluoride in SDG Goal 6 – "Ensure availability and sustainable management of water and sanitation for all" – of the Sustainable Development Goals (SDGs) (Loewe and Rippin, 2015; Hegarty et al., 2021) as one of the water contaminants. Whereas the SDG Goal 2 – "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" is related to food and food security (Loewe and Rippin, 2015), the word arsenic does not even appear. This is despite alarming As presence in rice for the global population (e.g., Abedin et al., 2002; Delowar et al., 2005; Dittmar et al., 2007, 2010; Potera, 2007; Rahman et al., 2008; Bhattacharya et al., 2009; Carbonell-Barrachina et al., 2009; Chou et al., 2014; Sandhi et al., 2017; Upadhyay et al., 2020; Saha et al., 2022). Moreover, there is no mention of As in the 2020 progress report of the SDGs (UN, 2020). The growing demand for food production and the consequent need for irrigation water and expansion of agricultural areas increases soil degradation, desertification, and erosion (increased by climate change and the related climate variability), which in turn increase As mobilization, primarily due to the general lack of organic matter in the soil (e.g., Belluck et al., 2003; Zhang et al., 2006; Ramakrishnan, 2015). Therefore, there is an immediate need for protection from As exposure, requiring an increase in respective research to mitigate As contamination, thus contributing to the SDGs Goals 2 (zero hunger) and 6 (clean water and sanitation).

This perspective article disseminates research, training, and knowledge related to the global As problem, including scientific aspects and mitigation technologies. Moreover, it deals with socioeconomic and environmental factors contributing to human development at national, regional, and international levels. This is expected to contribute to achieving the majority of the 2030 SDGs.

2. Where is As in global inter-sectorial goals and strategies?

2.1. Arsenic and the Universal Declaration of Human Rights

The Universal Declaration of Human Rights includes different human rights (UN, 2015b; UN, 2020), which has been accepted by nearly every state in the world and has inspired more than 80 international conventions and treaties, as well as numerous regional conventions and domestic laws, being the catalyst for improving human rights protections for groups such as disabled people, indigenous peoples, and women. Despite not being explicitly mentioned, the As problem is embedded in many declared human rights, the most important of which is the human right to water and sanitation (UN, 2002, 2010). For example, arsenicosis (Fig. 2) has become a human rights challenge as a poverty-aggravating or poverty perpetuating disease in Bangladesh (Islam, 2014). This is because once a poor person is affected by arsenicosis (with multiple organ complications), he/she loses his/her ability to work. Without any financial assistance, the poor household gets into perpetual poverty. Two types of poverty associated with the drinking of As-contaminated water exist in the example of Bangladesh (Barkat and Hussam, 2008): Type 1: Poverty-mediated arsenicosis, implying that the poor people are disproportionately highly affected by arsenicosis as compared to the non-poor, and Type 2: Arsenicosis-mediated poverty, suggesting that the aggravation of poverty due to arsenicosis where the As-affected poor people become poorer/pauper in the process due to economic, social, and psychological reasons.

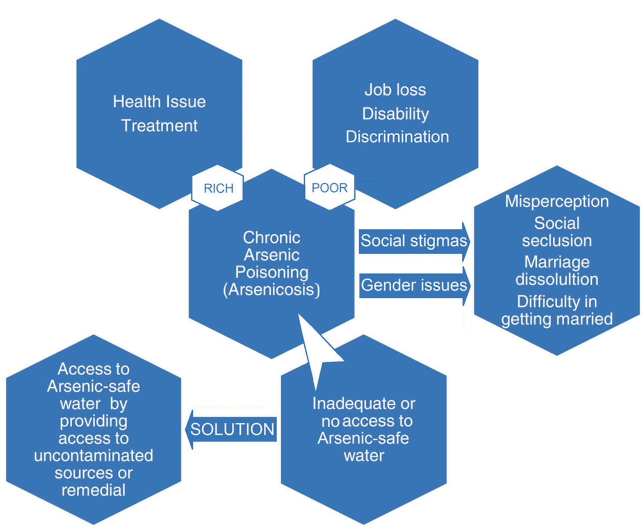

Fig. 2. Arsenicosis as a disease of poverty, social stigma and gender issue: Impacts of As contamination on the poor and marginalized sections of the society in many developing countries, viz. Bangladesh.

2.2. Arsenic and 2030 Sustainable Development Goals (SDGs)

On September 25, 2015, the United Nations General Assembly adopted the resolution 70/1, "Transforming our world: the 2030 Agenda for Sustainable Development" setting up 17 Sustainable Development Goals (SDGs) (UN, 2015a; UN, 2020). Among these goals, As topic is pertinent to the SDG 6 "Ensure availability and sustainable management of water and sanitation for all", Goal 3 "Ensure healthy lives and promote well-being for all at all ages", SDG 10 "Reduce inequality within and among countries", SDG 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development" and SDG 15 "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (UN, 2015a; UN, 2020). Furthermore, the provision of As-safe water – by enhancing food safety and security – contributes to SDG 1 "End poverty in all its forms everywhere", SDG 2 "End hunger, achieve food security and improved nutrition, and promote sustainable agriculture", and SDG 5 "Achieve gender equality and empower all women and girls" – addressing the disadvantages experienced by rural women in South Asia and Sub-Saharan African countries (e.g., Graham et al., 2016; UNESCO-WWAP, 2019) walking far from their homes to obtain As-safe drinking water or using a backyard well contaminated by As, as they are not supposed/allowed to walk outside to get As-safe water.

Replacing fossil fuels with locally available, environment-friendly renewable energy sources and technologies to cover the often high energy demand of the technologies for As removal from water links it to SDG 7 "Ensure access to affordable, reliable, sustainable and modern energy for all" and SDG 13 "Take urgent action to combat climate change and its impacts". This further triggers the need to "promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" and "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation", which are SDGs 8 and 9. There is a substantial nexus to SDG 4 "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" to which the umbrella contributes. However, unfortunately, the SDGs have been formulated as sectoral targets, despite that many topics (including the As topic) crosscut across multiple fields (and specific goals). They should instead be treated in an interconnected manner. This requires a reconsideration of all the respective nexuses within the framework of water, energy, environment, food, climate, and public health, which will be the key target of the proposed umbrella playing a landmark role in addressing the vast array of challenges that the 2030 SDGs encompass.

2.3. Arsenic in UNESCO's priorities and strategies

2.3.1. Global priorities

There is very little scientific data on As occurrence in groundwater in Africa, and even less regarding health effects, with some exceptions to South Africa and Egypt, Nigeria, Ghana, and Algeria (based on Web of Science database, Fig. 3). Since groundwater As is recognized as a global problem, the probability of As occurrence in groundwater at toxic levels in Africa is relatively high. Therefore, the problem may be of similar severity as in other continents. The current lack of information that undermines the severity can be attributed to the paucity of research and/or non-inclusion of As as a legal drinking or irrigation water analysis parameter. This underrepresentation of Africa in the As topic is also reflected in the fact that it was not before 2016 that African delegates participated in the international congress series "Arsenic in the Environment" or other As-related international events. Therefore, the As problem in Africa needs urgent attention, and the integration of Africa into the global network of As research and mitigation should be one of the key priorities.

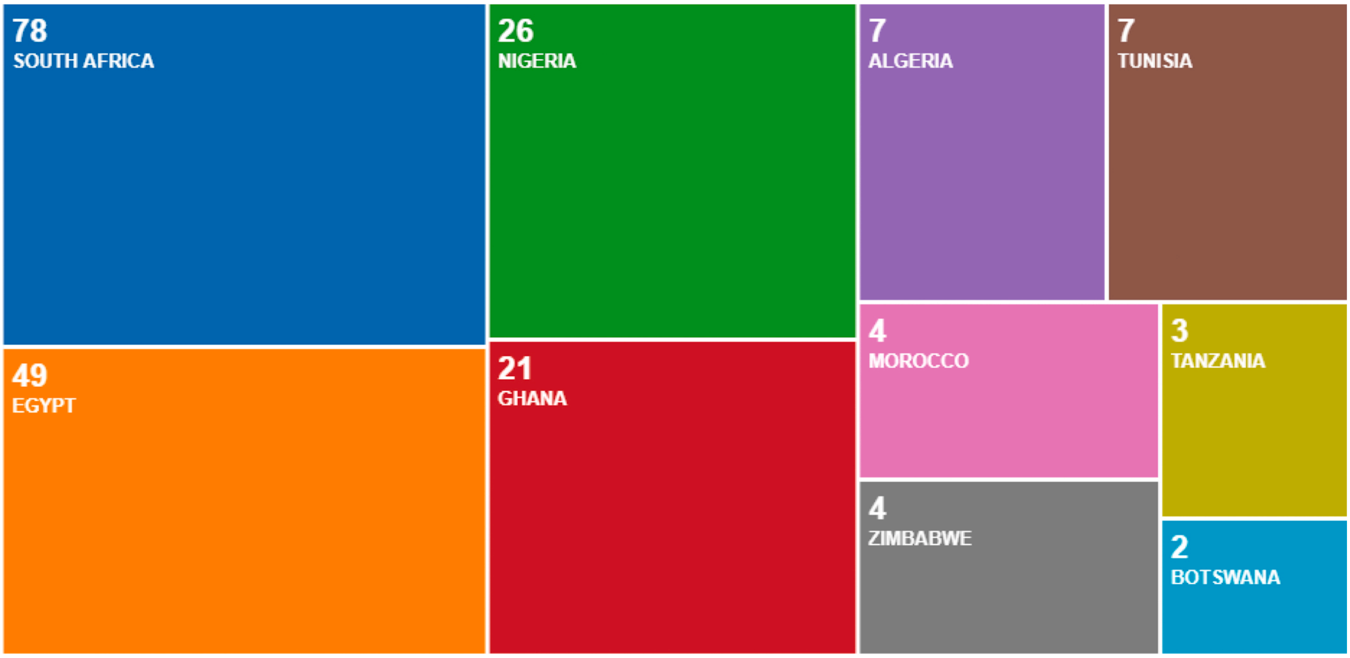

Fig. 3. Tree-map of the publications on As exclusively by authors from African nations based on the Web of Science database (April 11, 2021).

2.3.2. Gender equality

Gender equality is another priority of the proposed As umbrella. Regarding women, the goal includes three different components; (i) empowering women currently involved in fetching water for cooking and other household purposes in decision making at the community level, (ii) social issues and respective mental health problems due to skin lesions caused by As ingestion, and (iii) empowering women in science and engineering in the field of As research and mitigation through focused research and training.

There are numerous social aspects of As contamination and its mitigation, most of which are related to gender equality (e.g., in Bangladesh; APSU, 2006; Hanchett, 2006; Sultana, 2006; Mannan, 2006; UNESCO-WWAP, 2021). However, they have not attracted the attention they deserve, as the present focus is on scientific and technical issues; therefore, the aim must be not only to include them but make them another priority for the following reasons; (i) Since domestic water collection and use are traditional and significant responsibilities of women in many developing countries, women must be involved in planning from where and how alternative water sources will be used, or which treatment technologies or other mitigation measures are applied (e.g., APSU, 2006; Hanchett, 2006; Sultana, 2006; Mannan, 2006; Islam, 2014). However, unfortunately, women's voices are not often heard, particularly at local-level planning and decision making; thus, today, women have a very marginal role in most As mitigation efforts. This is despite women's interests, capacity to participate, and sense of responsibility for providing safe water and food to their families. (ii) Another "gender equality" As topic is the social discrimination and respective mental health issue associated with arsenicosis (e.g., skin lesions) in women (e.g., Hassan et al., 2005; Brinkel et al., 2009; Sarker, 2010). Accordingly, women with visible symptoms of arsenicosis suffer more discrimination than men in society: (i) while finding jobs where they are in contact with people, and (ii) during marriage arrangements, e.g., often they are abandoned or divorced by their husbands. Due to the reasons mentioned above and social stigma, today, women in many developing countries are not allowed to leave their house to obtain As-safe drinking water from community wells. Instead, they are forced to use As-contaminated water from their backyard tube wells (Fig. 2).

2.3.3. Changes that a global As umbrella can bring

The overarching aims and perspectives of the umbrella fall under UNESCO's National Science Sector, crosscutting two areas: "Environment" and "Science & Technology" (UNESCO, 2015a). Accordingly, in the "Water Sector" of the "Environment" area, they are closely linked to the "Division of Water Sciences" (UNESCO's International Hydrological Programme VIII: Water Security, IHP-VIII). In the "Science & Technology" area, the perspective goals are closely linked to the topic "Engineering" (through As removal/remediation technologies), where sustainable engineering, such as renewable energies or low-energy technologies for water treatment, are mainly targeted. Also, the umbrella takes into consideration the "Women in Engineering" agenda, where it "supports women scientists" through applications to existing scholarships for this target group and is committed to "promoting women's participation in decision making at the community level and policymaking processes", both being priority areas of UNESCO.

Further, it emphasizes the area "Science, Policy, and Society", where evidence-based solid research results in science and engineering are directly linked to benefits for the society. This will be attained through community participation (including women in improving social, health, and nutrition conditions and knowledge and information exchange with the stakeholders, viz., NGOs, authorities, and policymakers. Thus, the acquired information and knowledge will help in appropriate judicious, political, and professional decisions ensuring As-safe drinking and irrigation water supply and As-safe food production agricultural industry. Thus, the global As umbrella envisages facilitating knowledge exchange and providing vital scientific-based information to academia, industries, agriculture and mining, governmental and non-governmental organizations, international agencies for funding and technical cooperation, public health agencies, policymakers, regulators, and the broader public worldwide.

2.3.4. UNESCO's IHP VIII and Medium-Term Strategy for 2014–2021

The aforementioned As umbrella is closely linked with the "Division of Water Sciences" of IHP-VIII with its framework topic "Water Security" (2014–2021), crosscutting most of its formulated themes (IHP, 2016). This is through (i) promotion of international research in groundwater for a better understanding of As-contaminated aquifers and irrigated ecosystems (e.g., rice paddy fields), and (ii) mitigation through innovative methods/technologies and other approaches to provide As-safe drinking and irrigation water; this incorporates managerial and policy issues and social dimensions including further equal opportunities for women in decision making at the community level and in policymaking.

Theme 2 "Groundwater in a changing world" (IHP, 2017a) and Theme 3 "Addressing water scarcity and quality" (IHP, 2017b) are key themes related to the project as groundwater is the origin of the global As problem (through increasing international studies of (i) As origin, mobilization, distribution in aquifers, accumulation in the food chain and related health impacts, (ii) research on alternative water sources and mitigation measures, integrated with socioeconomic and environmental aspects, (iii) awareness programs and tools for stakeholders involvement [Focal Area 3.3], and (iv) improving legal, policy, institutional, and human capacity [Focal area 3.3]). The whole umbrella or umbrella topic is included in the Focal Area 2.4 "Promoting groundwater quality protection" as a specific objective ("increased support for the study of the origin, behavior, and processes occurring in groundwater environments polluted by hazardous substances of natural origin chemicals (arsenic, fluoride, etc.) and propose cost-effective soil and groundwater pollution remediation techniques").

The umbrella is also aligned to Theme 4 "Water and human settlements of the future" (through its objective of providing (arsenic-) safe drinking water for all, one of the significant challenges of the 21st century; IHP, 2017c). In particular, it is aligned to Focal Area 4.5 "Integrated development in rural human settlement" (through researching low-cost and locally produced technology for the treatment of As-contaminated water that can be operated and maintained by rural people) since approximately half of the population still lives in rural areas, in particular in Asia and Africa.

The umbrella is fully aligned to Theme 6 "Water education, key for water security" (through providing and facilitating research in science and engineering, education (formal and non-formal; IHP, 2017d), capacity building, awareness, and data to support global and regional management of As-contaminated groundwater resources and ecosystems (e.g., irrigated areas)). In addition, enhancing tertiary education and professional capabilities (Focal Area 6.1) is highlighted and provides the means covered by the other focal areas of this theme (6.2–6.4).

Concerning non-IHP UNESCO Priorities, given its transdisciplinary character, the umbrella is also linked to other Medium-Term Strategy (2014–2021) targets of UNESCO (2015b), including the global priorities Africa and Gender (already outlined in the Sections 2.3.1 and 2.3.2) and the Strategic Objectives SO 4 "Promoting the interface between science, policy and society and ethical and inclusive policies for sustainable development" and SO 5 "Strengthening international science cooperation for peace, sustainability and social inclusion" (through the targeted science for society approach in the As topic, as outlined in Section 2.3.3).

3. Perspectives of global As contamination research under the umbrella

3.1. Contribution to social, economic, and cultural development

Currently, research on the problems caused by As, in most cases, is simply focused on cutting-edge and breakthrough research in physical, chemical, technological, toxicological, and medical sciences. However, a long-term perspective is to provide an umbrella to conduct transdisciplinary international research and postgraduate and professional training, education, and awareness formation through a diverse and integrated global network and partnership on As-related topics. This includes (i) promoting the interface between science, policy, and society, ethical and inclusive policies for sustainable development, and (ii) strengthening international science cooperation for peace, sustainability, and social inclusion. In addition, it aims to collaborate with institutions and stakeholders interested in addressing the overarching As problem and seeks to provide a straightforward solution with considerable social impact and relevance.

Arsenic topics are addressed by dealing with the related problems within the SDGs and UNESCO's constitution and formulated goals. Specific priorities for long-term development objectives target are: (i) impoverished populations, (ii) Africa, (iii) women, and (iv) SIDS (Sudden infant death syndrome; e.g., Kinney and Thach, 2009; Moon and Fu, 2012). This includes researching better-adapted mitigation technologies and community-based strategies for the poor, better integrating Africa into the international As networking, and women's interests, needs, and capacity to participate in planning and decision-making regarding As-related topics in their community.

Knowledge management is an essential aspect of this process of putting science into action. The umbrella shall function as a global, regional, and country knowledge base where researchers, local institutions, stakeholders, policymakers, and education entities can exchange As-related information. This knowledge umbrella will also develop new ideas that would support policy and decision-making.

3.2. Specific challenges

(1) Improve As mitigation approaches for As-contaminated groundwater and irrigated ecosystems: Develop innovatively or improve/adapt/combine existing technologies and practices that will be applied globally to address society's significant challenges formulated in the SDGs. The platform will aim at state-of-the-art focused research on sustainable integrated solutions to As-contaminated water and food derived from its use for irrigation. This is a priority as As-contaminated water is a primordial base for other interrelated SDGs focusing on food/hunger, poverty, climate change, health, socio-economics, gender, etc., and meets the needs of the global communities we serve. This new knowledge must be disseminated to various stakeholders and international development bodies.

(2) Awareness creation and dissemination of existing and new knowledge regarding the As topic through education, training, and global networking: Awareness creation and knowledge dissemination on integrated sustainable solutions for the As problem is considered the vital link for a sustainable future. The umbrella will build a cadre of global professionals and decision-makers (including future professionals such as students) to build the skills, knowledge, and capacity to improve governance and sustainable development. This includes (i) latest research, (ii) technologies, (ii) concepts, (iii) models, (iv) toolkits, (v) data sharing and mapping platforms such as GAP (www.gapmaps.org), (vi) experiences from case studies, and (vii) the development of a decision support system, for driving the transition towards better-integrated management of As contaminated groundwater and irrigated systems. This includes developing and promoting respective policies and regulations that support more sustainable and integral approaches while considering the socioeconomic and cultural dimensions. Knowledge sharing would be done by organizing As-related transdisciplinary congresses and other events and through the Internet.

(3) Global networking and development of an evidence hub for research on As through (i) promoting, facilitating, and improving international transdisciplinary collaboration on scientific and technological aspects, in particular, between academic institutions, research centers, as well as industry, non-governmental organizations, public sector, and international organizations or groups, and (ii) establishing and facilitating contacts among national or regional academic organizations or networks around the world with a particular focus on global change and gender equity. This includes improved access to education resources; facilitating academic education and postgraduate and professional training; improving the institutional development and the capacity of universities and other research centers; joint research agendas; increasing scholarship opportunities and internships for researchers and postgraduates; developing curricula for teaching and training of professionals; development and implementation of collaborative projects; joint supervision of postgraduates; organization of joint international,

regional or national scientific events or training courses; common publication activities, etc. In addition, the promotion and support of a South-South and North-South research network facilitate collaborative action with specific partners to share knowledge to develop sustainable As mitigation and adaptation strategies are a priority.

(4) Create awareness and promote innovative integrated approaches to address the continuously increasing interdependencies of water (arsenic) with energy, food, public health, and most of the SDG areas (nexus), facilitating the management of As-contaminated water in a more coordinated manner instead of managing water and related topics separately. This will help identify synergies, reduce trade-offs, optimize resource use and improve management efficiency. This, in turn, will promote water, energy, and food security and contribute to the protection of public health, ecosystems, and climate.

4. Alignment with the UNESCO's priorities

To address the As-related challenges within the 2030 SDGs framework, priority areas and tasks have been defined, as shown in Fig. 4. It encompasses the As presence in the near-surface human environment, the implication of As-contaminated ground(water) in agri/aquacultural practices, treatment of As-related diseases, advances in As removal and immobilization technologies, and nexuses of As-related challenges within the 2030 SDGs, viz., clean water with the maximum up to 1 μg/L As, which is already being tried to achieve in Dutch drinking water utilities (Ahmad et al., 2020).

5. Roadmap for a sustainable solution

In the fields of water As research and developments to address the challenges of As within the 2030 SDGs holistically, the overarching future perspectives and goals should include the following (Fig. 5):

- Promote, develop and improve suitable actions, policies, and regulations that support more sustainable and integral approaches while considering the social, economic, and cultural dimensions.
- Create awareness and promote proven use and introduce new technologies or approaches. These should include, but are not limited to, (i) As removal/immobilization from/in water soils using physical, chemical, biological, and microbiological approaches, (ii) reducing the uptake of As by crops, (iii) removing As from industrial and other wastewater, and (iv) reusing for irrigation and artificial groundwater recharge purposes. This will help address groundwater As issues and lead to optimized use of this resource for humans and access to As-safe drinking and irrigation water resources in adequate quantity and good quality, thus contributing to the SDGs.
- Contribute to capacity-building human resource development, institutional strengthening, and policy reform for water, food, and related sectors within the SDGs.
- Establish and facilitate global contacts to and in between national or regional academic organizations or networks worldwide, focusing on global change and gender equity.
- Global networking for access to education resources and facilitating postgraduate and professional training; improve the institutional development and capacity of universities/research centers; exchange and training of professionals, researchers, and postgraduates for internships; development and implementation of joint projects; joint supervision of postgraduates; organization of joint international, regional or national scientific events or training courses; and joint publication activities.
- Innovating to feed the people with safe food not having As at toxic levels.
- Promote, facilitate, stimulate, and improve international transdisciplinary collaboration for promoting science and technology. This is particularly important between academic institutions, research centers, industry governments, and non-governmental organizations concerned with groundwater As.
- Develop tools, case studies, and insights on As-contaminated ecosystems for their management, development, and governance and disseminate their results widely.
- Integrate the gender dimension of science and technology, advocating the crucial role of women and the gender dimension in science and technology.
- Consider the discrimination of women by water, sanitation, and public health limitations.

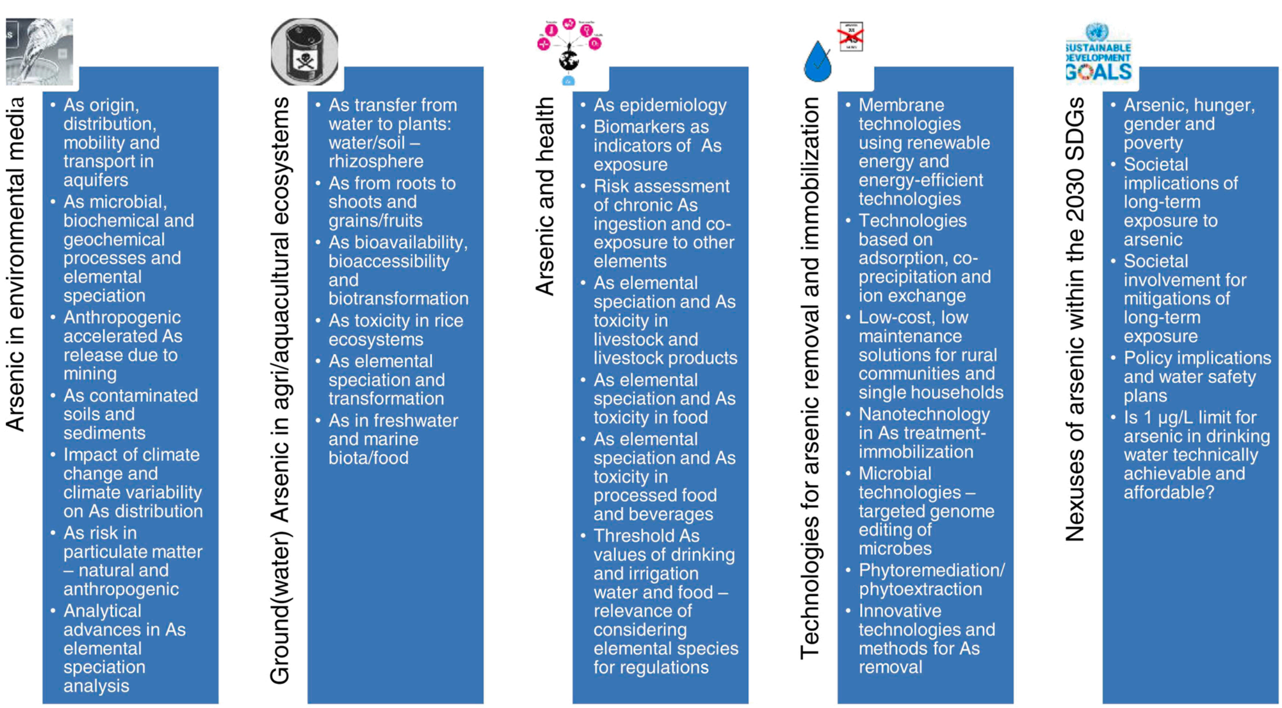

Fig. 4. Priority areas and corresponding tasks to address the global As challenge.

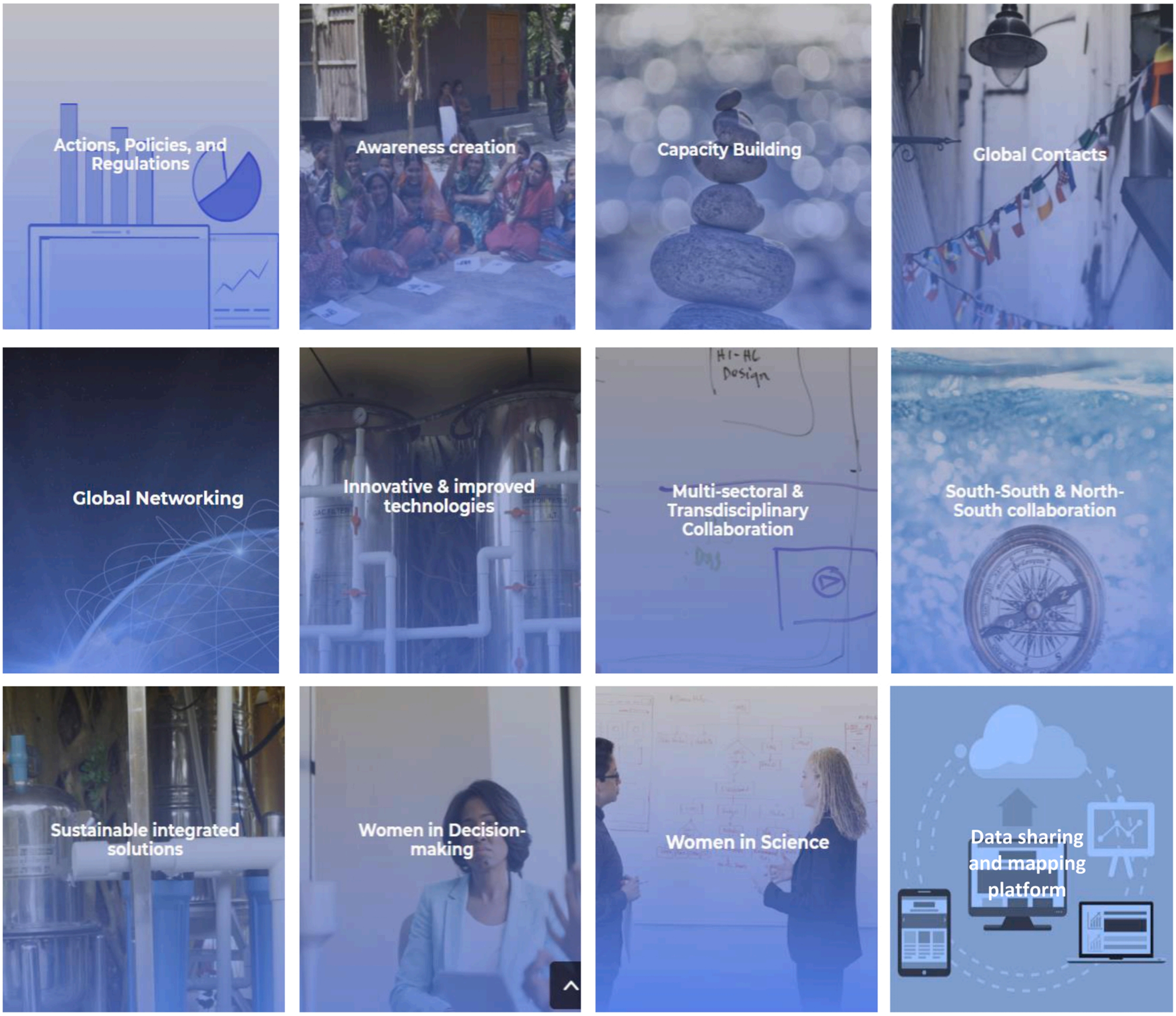

Fig. 5. Key elements for a sustainable solution of the global As problem.

- Consider that women and girls are critical in solving water, sanitation, and public health problems, which requires that men and women work alongside to address the related infrastructure and operations.

6. Conclusions

Two main aspects crucial in dealing with the global problem of As contamination are:

(1) *Arsenic research and global sustainability:* We consider that independent and transdisciplinary As research, and their nexus to the environment, food, public health, energy, and most SDGs are the pillars for protecting humanity from As uptake at toxic levels. Thus state-of-the-art, sustainable and integrated water-energy-food-climate-ecosystems solutions will significantly help safeguard drinking and irrigation water and food supply, protecting human health and well-being, environment, and climate.

(2) *Arsenic in a changing world:* We consider an increasing, economically profitable but sustainable, socially and environmentally sound food production and exploitation of natural resources, efficient management and use of water resources, where all societal groups can benefit through multiple future generations. This justifies the increasing importance of protection from As exposure in an increasingly dynamic world caused by human activity driven by population growth, industrialization, and changes in livelihood, which lead to an ever-increasing demand for geological resources, many of which contain As, viz. metal deposits, coal, and hydrocarbons.

CRediT authorship contribution statement

Jochen Bundschuh: Conceptualization, Writing original draft - reviews and editing, Methodology, Resources. **Nabeel Khan Niazi**: Conceptualization, Writing original draft – reviews and editing, Methodology, Resources. **Mohammad Ayaz Alam**: Writing – reviews and editing, Methodology, Resources. **Michael Berg**: Contribution of data/information, contributing to writing original draft – reviews and editing, Methodology. **Indika Herath**: Contribution of data/information, contributing to writing original draft – reviews and editing, Methodology. **Barbara Tomaszewska**: Contribution of data/information, contributing to writing original draft – reviews and editing, Methodology. **Jyoti Prakash Maity**: Contribution of data/information, contributing to writing original draft – reviews and editing, Methodology. **Yong Sik Ok**: Contribution of data/information, contributing to writing original draft – reviews and editing, Methodology.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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