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Department of Science and Technology
Ministry of Science and Technology
Government of India

Azadi Ka Amrit Mahotsav

Low-Cost Environmental Monitoring Sensors: Landscaping Review for the UK & India

December 2022

Disclaimer:

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"For us, protection of environment is an article of faith. We have natural resources because previous generations protected these resources. We must do the same for our future generations."

- **Prime Minister Narendra Modi**, 3 June 2017

"Health matters: we will enclose ongoing investigation regarding the current trends, research, issues, news related with air, water, soil quality in UK. Pollution is everybody's problem and a problem at all times."

- **Prof. Chris Whitty,** 17 February 2022

"Rivers are the arteries of nature and must be protected. Our inquiry has uncovered multiple failures in the monitoring, governance, and enforcement on water quality. For too long, the Government, regulators and the water industry have allowed a Victorian sewerage system to buckle under increasing pressure."

- **Environmental Audit Committee Chairman, Rt Hon Philip Dunne MP,** 13 January 2022

"In pursuit of cleaner air, we should pay as much attention to the design of our built environment as to the design of vehicles and transport services "

- **Dr Suzanne Barrington & Dr James Levine, University of Birmingham,** 18 December 2020

"One in six deaths in the world involves diseases caused by pollution, three times more than deaths from Aids, malaria and tuberculosis combined and 15 times more than from all wars, murders and other forms of violence"

- **UN Human Rights Council report,** 10 March 2022

"The Human Rights Council recognised, for the first time, that having a clean, healthy and sustainable environment is a human right. "

- Access to healthy environment declared human right by UN rights council | | UN News, October 2021

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Foreword

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As outlined in the India- UK 2030 Roadmap, bilateral partnerships to reduce emissions and improve climate resilience are an important step to realize the shared vision to build an environmentally sustainable and inclusive future together. It commits the two countries to build partnerships to take forward the collaboration, share best practices and low-cost climate appropriate technologies for adaptation and resilience.

Environmental pollutants are associated with rapid economic growth and monitoring them is a major global challenge. As the first step toward building solutions to combat this challenge, the Department of Science and Technology (DST), in partnership with Natural Environment Research Council (NERC) and the Engineering and Physical Sciences Research Council (EPSRC), commissioned this study to map the existing research landscape in low-cost environmental monitoring sensor (LEMS) development and application in both India and the UK.

This report underscores the significant impact that both water and air pollution is having in the UK and India, affecting human health, wildlife, and the natural environment. To address this issue, it is necessary for policymakers and decision-makers to have adequate data on the presence, quantity, and behaviour of pollutants in the environment in order to understand their impacts and inform suitable management approaches. This report focuses on low-cost sensor technology as a route to obtaining this data, for water and air pollutants. The report will be used to help determine future research priorities and areas for international collaborative research support in this area.

This work builds on the successful collaboration of DST, NERC and EPSRC on the Newton India-UK Water Quality programme. One objective of the Water Quality programme was the development of novel technology to enable better detection and monitoring of pollutants in Indian environments. The outcome has been innovative solutions to this challenge including low-cost, easy-to-use technologies that enable local communities to improve their water quality monitoring.

UKRI is keen to build on this partnership, establish further collaborative research investments and provide evidence of how this could lead to improvements in environmental monitoring and thus contribute to decision-making at a local and national level in both India and the UK. The aim of such technology is to ensure that a wide variety of users are able to detect and monitor pollutants in range of environments under a range of conditions/climates, with the potential to encourage and enable non-expert, community-led and citizen science monitoring initiatives.

Christopher Smith

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Secretary
Government Of India
Ministry of Science and Technology
Department of Science and Technology

05th September, 2022

FOREWORD

Monitoring environmental pollutants is essential to assess environmental conditions and trends and to report to national policymakers, international forums, and the public. However, continuous monitoring of pollutants is an expensive proposition, and hence only a few countries have been able to maintain such activities over the years. The development of low-cost environmental monitoring systems is thus the need of the hour and an unmet global challenge.

As a first step to address the problem, the Department of Science and Technology (DST), India and the Natural Environment Research Council (NERC) UK, and the Engineering and Physical Sciences Research Council (EPSRC) of UKRI launched a joint programme aimed at improving water quality by providing a better understanding of the sources and fate of emerging pollutants in both the countries and supporting the development of management strategies through the development of low-cost environmental monitoring sensors (LEMS). The programme bolsters India-UK 2030 Roadmap on reducing emissions and improving climate resilience.

This report maps the existing research landscape in LEMS development and their applications in India and UK. It is gratifying to note that several Indian laboratories are at the forefront of developing a variety of low-cost yet reliable sensors for water quality monitoring.

DST has a long-term vision of developing globally relevant programs in collaboration with strategic international partners. For example, the 'River Water Quality and Air Quality Monitoring' is a joint initiative of the DST in a bilateral

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collaboration, covering the entire gamut of real-time water and air quality monitoring. In conjunction with LEMS, the technological developments made under this programme would immensely benefit other flagship National Missions in India, such as the Namami Gange and Swachh Bharat.

I am delighted to note that concept of this report has been jointly evolved by the DST and NERC-EPSRC groups. I am confident that it will help determine future research priorities and pave the way for identifying areas for international cooperation between India and UK to address the problem of environmental pollution.

(S. Chandrasekhar)

Purpose of the report

Effective monitoring and management of environmental pollutants, which is associated with rapid economic growth and an artefact of modern societies, is a major global challenge. Of particular importance in addressing this issue is access for decision-makers to adequate data on the presence, quantity, and behaviour of pollutants in the environment to better understand their impacts at a local and national level and inform suitable management approaches. In addition, it is becoming more important for individuals to be able to access up-to-date information regarding the state of the natural environment to assess risks. This information can be obtained through rapid *in situ* data collection and continuous monitoring; however, such monitoring in wide-ranging situations requires innovative sensor technologies with a focus on usability and affordability (i.e., miniaturisation, low power, low cost, robustness, and ease of maintenance), with a view to enable a wide variety of users (especially non-experts) to monitor pollutants in a range of environments and conditions. As part of their collaborative strategy-setting, UKRI and DST have commissioned AquAffirm Ltd and IISc to undertake a mapping report on this topic with specific reference to India and the UK.

The aim is to map the existing research landscape in low-cost environmental monitoring sensor (LEMS) development and application in both India and the UK, identifying the key issues and challenges for both countries. This activity will be used to help determine future research priorities in this area.

Low-cost sensor technology can potentially revolutionise the area of pollution monitoring by providing high density spatiotemporal pollution data. Such data can be utilised for supplementing traditional pollution monitoring, improving exposure estimates, and raising community awareness about pollution. However, data quality remains a major concern that hinders the widespread adoption of low-cost sensor technology.

Financial constraints often limit scientists' ability to deploy dense networks of conventional commercial instrumentation. Rapid growth in the area of Internet-Of-Things (IoT) and the maker movement is paving the way for low-cost electronic sensors to transform global environmental monitoring.

Accessible and inexpensive sensor construction is also fostering exciting opportunities for citizen science and participatory research (Chan, 2021).

Future research (Mao, 2019) to unleash the full potential of LEMS (low-cost environmental sensor) networks are: (1) improvement of links between data collection and downstream activities; (2) the potential to broaden the scope of application systems and fields; and (3) to better integrate stakeholder engagement and sustainable operation to enable longer and greater societal impacts.

Challenges for the monitoring sensor arise from the fact that hardware oftentimes has a short-life span resulting in a short working time of sensor, there is still a high need for maintenance including calibrations, battery replacements etc. Also, there is usually a large amount of data retrieved that can be a challenge to assess but must be analysed and interpreted. Other associated issues are the hidden costs, test strips, calibration fluids, data analysis, and the need to make sensors robust enough to deploy in harsh environments; this can be expensive and increase the sensor cost significantly.

Executive Summary

Effective monitoring and management of environmental pollutants which are associated with rapid economic growth and an artefact of modern societies, is a major global challenge. To address this issue, it is necessary for policymakers and decision-makers to have adequate data on the presence, quantity, and behaviour of pollutants in the environment to understand their impacts and inform suitable management approaches. *Data* is the first step to *intelligence* which is one of the key foundations that viable, long-lasting, and impactful policies are built upon.

This report focuses on low-cost sensor technology as a route to obtaining this data, for water and air pollutants. This technology can potentially revolutionise the area of pollution monitoring by providing high density spatiotemporal pollution data. Such data can be utilised for supplementing traditional pollution monitoring, improving exposure estimates, and raising community awareness about pollution. The purpose of this report is to map the existing research landscape in low-cost environmental monitoring sensor (LEMS) development and application in both India and the UK, identifying the key issues and challenges for both countries. To do this, the authors have used both secondary (desk-based) and primary research methods, the latter being through interviews with experts and policymakers working in the field. This activity has been commissioned by Natural Environment Research Council (NERC), Engineering and Physical Sciences Research Council (EPSRC) and India's Department of Science and Technology (DST) and funded by UKRI India. This report will be used to help determine future research priorities and areas for international collaborative research support in this area.

The report underscores the significant impact that both water and air pollution is having in the UK and India, affecting human health, wildlife, and the natural environment. The report then focuses on actual LEMS systems and networks already deployed and under development in the two compartments (water and air) and two countries (UK and India).

LEMS for Water Pollution – UK, India

Challenges

Based largely on interviews with researchers, the report has highlighted several challenges faced by users of current LEMS systems. In the water space, challenges identified included short hardware lifespan resulting in a short working time of sensor, high need for maintenance (including calibrations, battery replacements, etc.) and hidden costs: even though the sensors are generally manufactured with inexpensive materials, often the monitoring destination requires environmental robustness that add additional ('hidden') costs to sensor operation, making it more expensive. Moreover, the large amount of raw data extracted can be a challenge to analyse and comprehend, which is an additional hidden cost making the sensor more expensive.

Other key technical challenges identified by the experts we spoke with include:

- Reliability and robustness (electronics should not be allowed to degrade into rivers) – it was suggested that biodegradable materials be explored
- Need for regular calibration was a particular challenge for many users; the development of calibration-free sensors (such as the pH sensor developed by ANB sensors, Cambridge) was highlighted as desirable
- Trade-off between high-performance precision and low-cost portability: is it possible to have both?
- Deploying to regions of harsh environmental conditions: robustness was highlighted as a quality of particular importance.

Key parameters of importance

Several researchers recognised the significance of focusing on emerging contaminants through supporting development of highly sensitive (low limit of detection) LEMS for measuring:

- Emerging contaminants such as persistent chemical pollutants, nanomaterials, personal care products and fragrances, pharmaceuticals, synthetic hormones, and microplastics,
- Antimicrobial resistance (AMR) in natural aquatic systems (reservoirs, rivers), and effluent discharge from water treatment plants to assess the effectiveness of AMR removal and resulting loads in treated waters

Gaps

Researchers identified several other gaps where emerging technologies could be additive, including:

- Development of newer sensor materials, architecture, fabrication, packaging, and data analysis should be undertaken with industry collaboration.
- Networking of sensors and use of artificial intelligence (AI) tools and algorithms for environmental decision-making and policymaking for different stakeholders and at different scales.
- It was recommended that more industry-academic funding programmes be implemented.
- Finally, one research team interviewed has previously produced a nice table recognizing the considerations involved with implementing LEMS networks for water contaminants:

Table ES-1. Considerations regarding implementation of LEMS networks

Application scenarios ● What do we need low-cost sensor networks for?
Stakeholders and partnerships ● Who is involved in operating sensor networks and for what purpose? ● How and why do these stakeholders collaborate? What are their collaborative roles?
Citizen science and public participation ● How can citizen scientists be involved? ● What incentives are there for public participation in sensor networks?
Context ● How can sensor networks be adapted to different physical, socio-economic and sociotechnical contexts?
Technical capacities and behaviours ● How and in what ways might we increase technical capacities or change human behaviours inorder to use sensor networks? ● How do users operate and interact with sensor network applications?
Decision and policymaking ● How can collected data feed into decision and policy making at different levels?
Finance and operational mechanism ● How should sensor networks be funded? ● How can sensor networks be made more financially and politically sustainable?
Evaluation and impact ● How can we define and evaluate 'successful' sensor network applications? ● How can we create pathways to achieve long-term societal impact through sensor network applications?

Adapted from Feng Mao, J.C., Wouter Buytaert, Stefan Krause, David M. Hannah, Water sensor network applications: Time to move beyond the technical? Hydrological Processes, 2018.

Complementarity

- Developing sensors focusing on **antimicrobial resistance** is an area of interest to researchers from both UK and India and certainly warrants consideration as a point for future support and collaboration. Indeed, the DST-funded AMRflows project involving IIT-Madras, and University of Birmingham is an example of a collaborative project focused on this area.

i-LEMS

Finally, one researcher commented on the importance of bringing intelligence into play when implementing LEMS networks, to create "i-LEMS" systems where data is only part of the answer and intelligent implementation the other:

'Intelligent decision making with human-machine interplay and with science, policy, and public interplay. Challenges to modelling, forecast interpretation and understanding of relationships include being able to track dynamics driven by external factors. Funding should go to basic research, applied research, cofound with the industry to do the next step, at the same time we need to fund policymakers and local authorities to be able to have the capacity to use technology, train the personnel, and develop systems able to use the technology.'

LEMS for Air Pollution – UK, India

Challenges

Current challenges to the use and development of low-cost environmental sensors for air quality monitoring include:

- Although low-cost sensors provide a better spatiotemporal analysis than traditional monitoring methods there is still the need to produce and install a much bigger network of sensors in order to get closer to reaching the ground truth.
- In some situations where harsh environmental conditions are observed, there is still a need to develop sturdy and robust hardware capable of supporting the sensor; otherwise, it usually gets destroyed or lost.
- The hardware often has a short lifespan resulting in a short sensor working time or it gets dirty and dusty, which, without an in-built auto-clean property, results in unreliable readings and results.
- There is a high need for maintenance including frequently calibrations, replacement of batteries, cleaning of the device.
- Networks with a large number of sensors that take measurements within short intervals of time produce a large amount of raw data that can be difficult to analyse and produce into factual results.
- Hidden costs once again represent an issue, adequate hardware or data processing software might add to the value of the sensor.

Key recommendation focused on importance of satellite data from space-based instruments to help derive long-term pollution trends to monitor emissions and inform policies to reduce pollution, with their results confirming that vigilance and urgent action are needed across the globe to reduce air pollution levels. Satellite observations contribute to the tracking of seemingly invisible pollutants; a long and consistent record of observations is vital for assessing the success or inadequacies of current mitigation measures.

Section 1: Introduction – Pollution: A Global Issue

Environmental pollution, particularly that affecting air and water, are global issues causing a significant impact on human health and the wellbeing of wildlife and the natural environment. The widespread prevalence of environmental pollution began with the birth of the industrial revolution in the18th century and has only accelerated since. As economies, industrialization and populations have continued to grow worldwide, so too has environmental pollution, leading to a serious global problem that continues to affect biodiversity, ecosystems, and human health worldwide. It is directly implicated as a key cause of climate change.

Air pollution is widely recognized as a major threat to public health and economic progress and remains high on the global agenda, with the World Health Organization (WHO) estimating that 4.2 million deaths annually can be attributed to outdoor air pollution (Organization, 2016). The World Bank cites air pollution as the leading environmental risk to health, costing the globe an estimated $8.1 trillion in 2019, equivalent to 6.1 percent of global GDP (Araujo, 2011).

Water pollution resulting from agricultural and manufacturing activities is equally debilitating: globally, over 3 billion people are at risk of disease because the water quality of their rivers, lakes and groundwater is unknown, due to a lack of data; unsafe water sources are responsible for 1.2 million deaths each year globally (Araujo, 2011).

The scale of this detrimental impact has acted as a call to action for global organisations. Indeed, the United Nations Sustainable Development Goal Target 3.9 specifically mentions a focus on reducing morbidity and mortality from air and water contamination. Pollution of this magnitude has also had a dramatic impact on the natural environment, being a primary cause of what scientists are calling the "sixth mass extinction". In a recent PNAS paper, the biologists argued that this "may be the most serious environmental threat to the persistence of civilization, because it is irreversible" (Gerardo Ceballos, 2020).

This global reduction in biodiversity -- or "biodiversity collapses" -- will have a long-term impact on human civilization if it cannot be managed and brought under control. A key objective, therefore, must be to bring pollution globally under control.

"Decisions made in the next few years will determine whether our existence on Earth as we know it will continue or collapse because of human activity. The need to change the ways societies interact with and affect the environment becomes more urgent as the tangible impacts of a planetary crisis accumulate - generating daily headlines about extreme weather events, pandemics, pollution, and a mounting shortage of essential natural resources" (United Nations Environment Programme (UNEP)).

Background: United Kingdom

Water pollution

Water pollution in the UK remains a substantial environmental and health issue. Indeed, a recent report from the Environmental Audit Committee (EAC) warns of a 'chemical cocktail' of sewage, slurry and plastic polluting English rivers, putting public health and nature at risk (Commons, 2022).

It is clear, however, that rivers in England are in a mess. A 'chemical cocktail' of sewage, agricultural waste, and plastic is polluting the waters of many of the country's rivers. Water companies appear to be dumping untreated or partially treated sewage in rivers on a regular basis, often breaching the terms of permits that on paper only allow them to do this in exceptional circumstances. Farm slurry and fertiliser run off are choking rivers with damaging algal blooms. Single-use plastic sanitary products—often coated with chemicals that can harm aquatic life—are clogging up drains and sewage works and creating 'wet wipe reefs' in rivers. Revolting 'fatbergs' as big as blue whales are being removed from sewers, costing companies and their customers in the region of £100 million a year. Not a single river in England has received a clean bill of health for chemical contamination. Disturbing evidence suggests they are becoming breeding grounds for antimicrobial resistance.

House of Commons Water Quality in Rivers January 2022

https://committees.parliament.uk/publications/8460/documents/88412/default

"*Scotland has the largest number of high-quality rivers - with up to 66% in good condition. In Wales, the figure is 40%, in Northern Ireland it's 33% and in England it's just 14%."*

Water pollution: How clean are the UK's rivers and lakes?
- BBC News, 13 Jan 2022

According to that report, only 14% of English rivers meet good ecological status, with pollution from sewage, agriculture, roads, and single-use plastics causing a dangerous 'chemical cocktail' coursing through our waterways. Not a single river in England has received a clean bill of health for chemical contamination.

The report goes on to state that it is currently difficult to get a complete overview of the health of rivers due to "outdated, underfunded and inadequate monitoring", with budget cuts to the Environment Agency hampering the ability to monitor water quality in rivers and detect permit breaches or pollution incidents caused by the water industry and farming. In addition, river quality monitoring does not routinely identify emerging issues such as microplastics, persistent chemical pollutants or anti-microbial resistant pathogens flowing through rivers.

Sewage discharge is a key issue: the impact of wastewater from sewage treatment works and sewer overflows is preventing 36% of water bodies from achieving good ecological status. The EAC was alarmed at the extent of sewage discharge and of misreporting and large spills by water companies. To understand the scale of the problem, Figure 1 shows an Environment Agency tabulation of the number of pollution incidents in the UK from sewerage and clean water assets, and associated trend for the nine water and sewerage companies (Wessex Water, Severn Trent Water, United Utilities, Yorkshire Water, Anglian Water, Northumbrian Water, Thames Water, Southern Water, and South West Water) from 2005 to 2020, showing that the total number of incidents has remained at around 2000 per year since 2016.

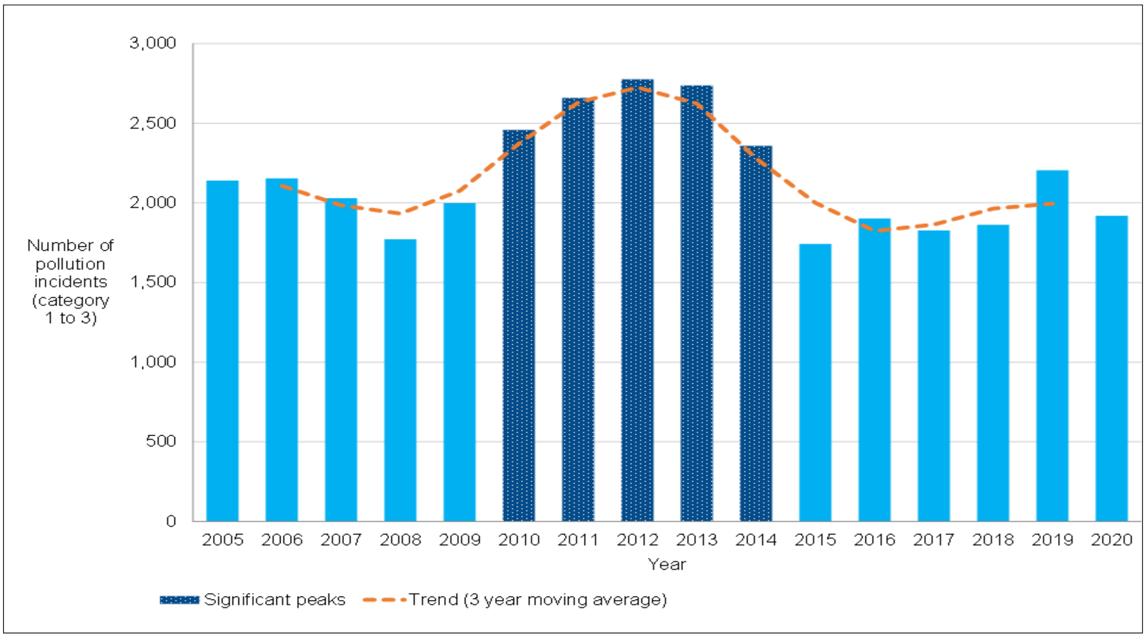


Figure 1. Number of pollution incidents in the UK from sewerage and clean water assets, and trend for the nine water and sewerage companies, 2005 to 2020 (Environment Agency) (Pollutants, 2018).

The EAC report goes on to state that the actual number of sewer overflow discharges may be much higher than those reported by the water companies to the Environment Agency. Water companies in the UK appear to be dumping untreated or partially treated sewage in rivers regularly, often breaching the terms of permits that only allow this in exceptional circumstances. An urgent review of water companies' self-monitoring is needed, the report concludes.

Public health risks

Pollution resulting from sewage discharge significantly increases health risks to the public. Bacteria such as salmonella and cyanobacteria found in sewage and animal slurry can cause illness. Yet few river users have the information and tools available to make informed decisions about when it is safe to use rivers downstream of storm overflows and wastewater treatment works. The EAC report recommends that the

Environment Agency work with water companies to ensure that easily accessible information on sewage discharges, as near to real time as possible, is made publicly available. Improved monitoring tools (networked sensors communicating to publicly available smartphone apps, for example) could help in achieving this objective.

Agricultural pollution

Often driven by rainfall and how we manage agricultural land, rural diffuse pollution occurs when nutrients, pesticides, faecal bacteria, chemicals, and fine sediments are lost from the land into local streams, rivers, lakes, and groundwater. This represents a cost to the farm business and has a major impact on the natural environment. Indeed, the EAC report notes that the impact of rural diffuse pollution is the most common form of pollution preventing rivers from achieving good ecological status. Intensive livestock and poultry farming is putting enormous pressure on certain catchments, such as that flowing into the River Wye, resulting in an increase in the river's phosphorus levels. The Committee has called for each catchment to have a nutrient budget calculated. Pollution must then be progressively reduced from all sources in the catchment until it falls below the capacity of the river to handle the nutrients. New poultry farms should not be granted planning permission in catchments exceeding their nutrient budgets. Low-cost monitoring sensors and innovative strategies for connecting, collecting, and communicating are needed.

Air pollution

Air pollution – primarily caused by road traffic – is one of the UK's biggest killers and is responsible for an estimated 36,000 premature deaths each year, according to a 2018 report by the Committee on the Medical Effects of Air Pollutants. Like most crises, it's the poorest and most vulnerable who suffer the greatest impact from pollution (Pollutants, 2018). One of the pollutants caused by road traffic, nitrogen dioxide (NO_2), is a toxic gas which inflames the lining of the lung and reduces immunity to lung infections such as bronchitis. Recent evidence suggests exposure could also increase the risk of being hospitalised with COVID-19. Despite government benchmarks on acceptable levels of pollution, those levels are frequently breached (Affairs, 2015). Continued vigilance and more comprehensive surveillance are necessary to identify pollution "hot spots" and to ensure recent improvements in UK air quality continue. Airborne tyre residues/particles from cars are key elements of pollution where tyre wear produces up to 1000 times more (compared to 4.5 mg per km emitted from a vehicle exhaust pipe) harmful particulate matter pollution than car exhaust.

Background: India

Water pollution

Water pollution is a serious problem in India and in many cases, the sources of water have been rendered unsafe for human consumption as well as for other activities, such as irrigation and industrial needs. The degraded water quality can also contribute to water scarcity as it limits its availability for both human use and for the ecosystem.

In 1995, the Central Pollution Control Board (CPCB), India has identified severely polluted stretches on major rivers in India. Not surprisingly, most of these stretches were found in and around large urban areas. The high incidence of contamination near urban areas indicates that the industrial and domestic sectors' contribution to water pollution is much higher than their relative importance implied in the economy. Agricultural activities also contribute in terms of overall impact on water quality. Besides a rapidly depleting groundwater table in different parts, the country faces another major problem on the waterfront, namely groundwater contamination, a problem which has affected many states. Geogenic contaminants, including salinity, iron, fluoride, and arsenic have affected groundwater in many districts spread across several states (IDFC, 2019).

Uncontrolled urbanization in many areas has also led to generation of sewage water. In the urban areas water is used for both industrial and domestic purposes, from waterbodies such as rivers, lakes, streams, wells, and ponds. About 80% of the water used for India's domestic purposes is passed out in the form of wastewater. In most of the cases, this water is not treated properly and as such it leads to tremendous pollution of surface-level freshwater. Water contaminants which are geogenic (natural), as opposed to man-made, also have an impact on health. Arsenic and fluoride contamination in ground water is a significant challenge that India must combat, with many parts of the country affected.

Air pollution

Long-term exposure to unhealthy air increases the risk of respiratory diseases, particularly in children. Knowing pollution sources is essential before undertaking each city's air quality challenge and can be handled by initiatives for clean air by the government or private sector.

India has about ~0.8 monitors per million people and there is a need for increased stations with real-time monitors, especially in rural areas. Based on recommendations made by the 15th Finance Commission to the Government of India, 42 "million-plus" Indian cities received dedicated air quality management funds in 2020. Urban Local Bodies (ULBs) received budgetary allocations of INR 2,200 crore in 2020 and INR 2,217 crore in 2021. Though these grants are critical for mainstreaming air quality in municipal governance, they do not cover all the cities, transport and industrial sectors (Council on Energy, 2021). The consolidated list of activities launched by the National Clean Air Programme (NCAP), launched in 2019, is shown in Figure 2. The number of Indian cities showing better air quality increased to 96 in 2020 from 86 in 2019 due to such an initiative by National Clean Air Programme (Standart, 2021).

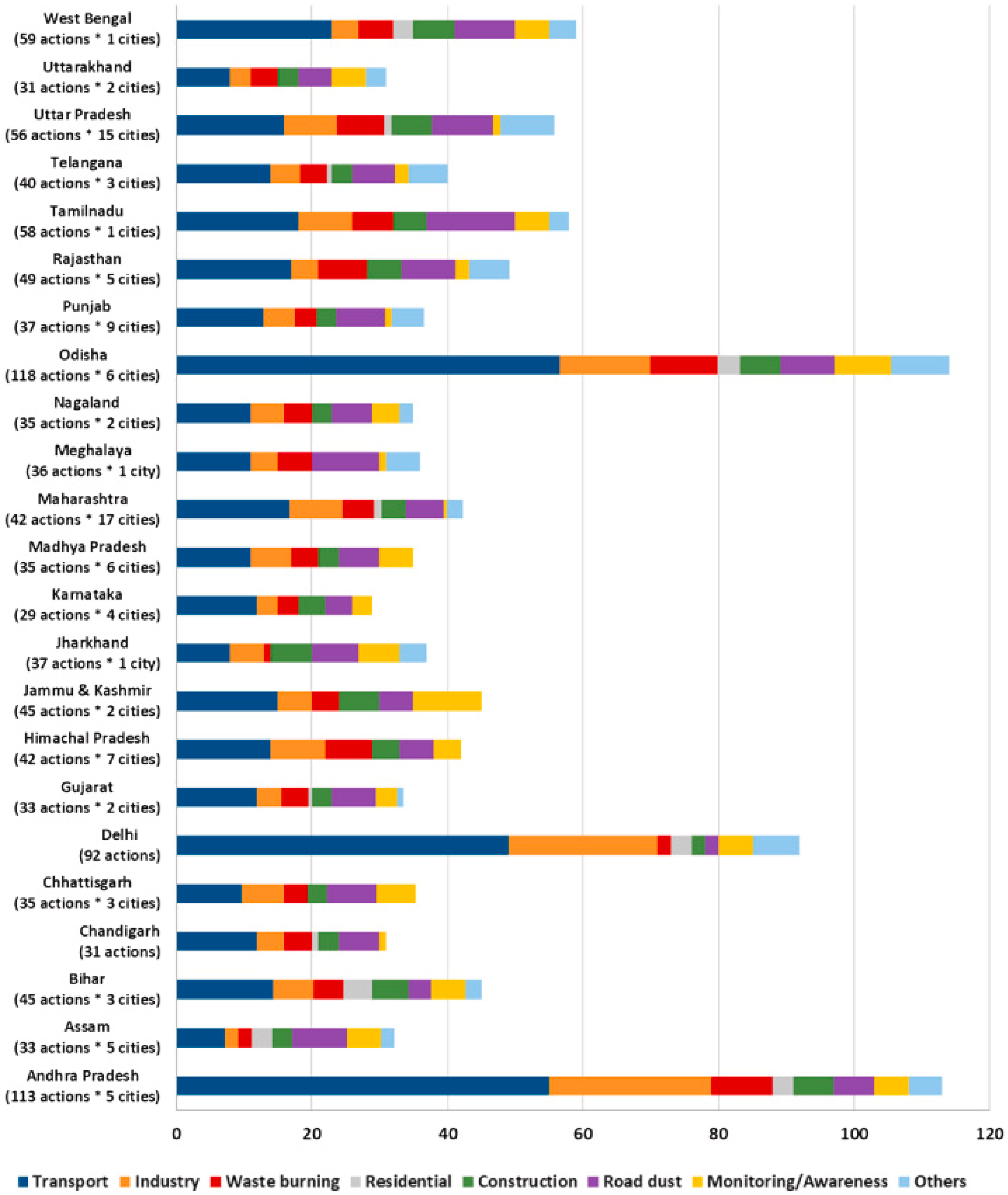


Figure 2. Average count of action points by sector mentioned in the NCAP clean air plans by state (Ganguly, 2020).

It is imperative that for both air pollution and water pollution in both India and the UK, new strategies are needed to monitor, manage, and mitigate these problems to reduce their impacts on health and the natural environment.

Section 2: LEMS for monitoring water pollution

Background

Water is not only a requirement for all living organisms but also an essential element for the efficient functioning of the environment, biodiversity and the economy; nevertheless, humans continue to ignore its importance by polluting it. Water pollution represents the contamination of water bodies (*i.e.,* streams, rivers, lakes, aquifers, seas, oceans) by harmful substances. According to the World Health Organisation (WHO), around 3.5 million people die each year due to water related diseases. In 2017, UNESCO estimated that, at a global scale, around 80% of wastewater is returned to the environment without adequate treatment, ending up destroying the already small number of freshwater sources (Agency, 2018).

India and the UK have collaborated in the water quality area previously. The India-UK Water Quality programme was a 3-year programme (2018-2022) jointly funded by UKRI's Natural Environment Research Council (NERC) and Engineering and Physical Sciences Research Council (EPSRC), and India's Department of Science and Technology (DST). The programme supported novel research aimed at improving water quality by providing a better understanding of the sources and fate of different pollutants and by supporting the development of management strategies and technologies to reduce pollution levels. Following an open competition, eight India–UK collaborative research projects were funded and commenced working in January 2018. The projects addressed a range of priority water quality issues. The goal was to enable collaborations that could lead to more science outputs that support policy- and decision-making (Hydrology, 2018).

UK

UK faces challenges when it comes to water quality; the Environment Agency reported that in 2016 around 86% of river water bodies in England did not reach good ecological status. Moreover, in 2015 around 38% of all fish tests and 61% of all invertebrate tests in rivers failed due to disease caused by pollution (UK, 2021).

Water pollution in the UK has been described as a chemical cocktail of untreated sewage, agriculture fertiliser and pesticides, and road pollution “run-off”. Many different contaminants are currently polluting the water; these contaminants can be synthetic or biological and many of them are man-made. The main concerning water pollutants include nutrients such as phosphorus and nitrates, detergents, oils, raw sewage, microorganisms, plastics, other solids, and chemicals (i.e., fluoride, arsenic, iron, manganese, cadmium, lead, nickel, zinc, organo-metal tributyltin, pesticides such as cypermethrin and metaldehyde, mercury, brominated flame, retardants polybromodiphenyl ethers (PBDEs), to a lesser extent certain perfluorinated chemicals such as: perfluoro-octyl-sulfonate (PFOS) dioxins and dioxin-like polychlorinated biphenyls (PCBs), occasional hexabromocyclododecane (HBCDD) and Polyaromatic hydrocarbons (PAHs)) (Agency, 2018). Emerging pollutants (Arman, 2021) represent the contaminants that are not yet regulated but may be of concern for human and environmental health; these include caffeine, nicotine and other metabolites, brominated flame retardants and surfactants, byproducts and industrial additives, nanomaterials, personal care products and fragrances, pharmaceuticals, and synthetic hormones, including veterinary medicine, and water treatment byproducts.There is ongoing concern regarding pollutant release from sediments in sewer systems which affects water quality (McGregor, 1993).

The consequences of water pollution are devastating. Agriculture alone (including the use of fertilisers and pesticides, contamination with manure from livestock and soil erosion) is responsible for 50% to 80% of all water pollution [19, 20]. Organic waste originated from farming and the sewage wastewater system is eliminated and decomposed by bacteria in water, requiring oxygen. In the case of having excessive organic waste in the water being decomposed, there is the chance of depleting that water of oxygen, therefore having a negative impact on aquatic fauna and flora that require oxygen for survival (Parliament, 2017). Nutrients such as nitrates or phosphorus also have a negative impact on water quality since they promote eutrophication, resulting in algae blooms that at times cover the entire surface of water, depleting it of sun-light and oxygen. Once the water body is fully depleted of oxygen it becomes a dead zone, where life is no longer supported (Parliament, 2017). Persistent Bioaccumulative and Toxic substances (PBTs) (e.g., persistent organic pollutants (PoPs) such as industrial chemicals or heavy metals) represent a threat to life too; they are known to affect aquatic and human health and contribute to biomagnification and bioaccumulation in the food-chain (Kay, 2009; Johnston, 2021). Physical pollution of water occurs when substances cannot dissolve or settle in water; it’s the case for fine particles like clay or sand, nanoparticles or even microplastics. These are known to obstruct sunlight from penetrating the water body in question, once again leading to depletion of oxygen levels and disruption of the food chain (Parliament, 2017). Moreover, there is a synergistic relationship between pollutants and human actions that cause destruction of ecosystems. Pollution in combination with overfishing, physical disturbances, climate change, bloom of invasive species and dead zones result in an increase in temperature and acidification of waters. Acidification of waters can cause the corals to bleach and negatively impact other marine invertebrates. Dissolved pollutant transport over the ground surface is a major contributor to water pollution as well (Zhang, 2020).

The Water Framework Directive (WFD) was created by the European Union (EU) with the end goal of helping prevent further water environment deterioration and to increase water quality in general. The issues are addressed by managing water in natural river basins rather than by administrative boundaries and the plans are set out as River Basin Management Plans (RBMPs) (Commons, 2022). After Brexit, the UK replaced this directive with new ones: Water Environment (Water Framework Directive) (England and Wales) Regulations 2017, Water Environment (Water Framework Directive) Regulations (Northern Ireland) 2017, Water Environment and Water Services (Scotland) Act 2003 (Instruments, 2017).

In order to achieve a "good status", water must meet the required environmental quality standards (EQS) for 4 different parameters (*i.e.,* biological, physical-chemical, chemical and hydro morphological) (Instruments, 2017). Assessments of water quality started to include measurements for uPBT (ubiquitous, persistent, bioaccumulative and toxic) such as mercury, brominated diphenyl ethers (pBDE), tributyltin and certain polyaromatic hydrocarbons (PAHs), chemical targets, suspect and non-target analysis, *in vitro, in vivo and in situ* bioanalytical examinations (in fish, crayfish, and mussels), tailored sampling techniques, standardised protocols for chemical, toxicological and ecological assessments, combined with systematic evidence evaluation technique. As of September 2021, the Environment Agency revealed that 0% of England's water bodies meet good chemical status. The percentage was never this low, but due to changes to the assessment methods and parameters, for the first time, it finally reveals the real situation (Agency, 2021). The Environmental Agency (England and Wales), the Northern Ireland Environment Agency, and the Scottish Environment Protection Agency response to protect UK waters includes directly working and investing in sewage/water companies promoting the good state of its materials, working with farmers to support environmentally friendly farming, as well as working with the government, policymakers, and NGOs.

The Environment Act 2021 (Governance, 2021) addresses updated water related legislations. For the first time, it is now a statutory duty to have a management plan for drainage and sewerage, by making companies evaluate the capacity of their networks. By doing so, there is a better opportunity to create risk assessments for the present drainage and wastewater issues, their impacts on the environment, allowing for long-term planning that is extremely important to aid in the ability to fight extreme weather events or even flooding. This management plan will also provide companies with information on how to invest more efficiently. The statutory water resources management plan was amended to establish a better and more effective collaboration with water companies to manage supply and demand, be more efficient in a drought scenario, as well as a better understanding of environmental needs resulting in environment improvement. It is a fact that storm overflows cause harm to the environment and communities, and it is a government priority to reduce their consequences. Therefore, the Environmental Act 2021 requires the government to publish by September 2022 a statutory plan with the purpose of reducing discharges from storm overflows. Also, water companies and the Environment Agency must report and monitor the annual storm overflow activity and the water quality upstream and downstream of the discharge, with the purpose of acting as foundation data for future policy decisions on this topic. Regarding the water industry regulation, the current process by which the government modifies water and sewage company's licence conditions is being modernised, creating room for Ofwat (Water Services Regulation Authority) to positively develop how it regulates water companies through a licence with a modern modification process; the process currently in place has been found to impede responsiveness to industry legislation. Concerning water abstraction, the aim is to reduce the risk imposed by it and the damage that may occur to the environment. In the past, availability of fluctuating waters was not taken into consideration when creating some of the licences, often resulting in excess water being extracted from the environment. Inorder to tackle this issue, starting on the 1st of January 2028 new measures make possible the revocation/cancellation of permanent abstraction licences without liability for compensation, in the case of the licence being constantly under-used or inorder to protect the environment if needed. These new measures are only to be put in place by the Environment Agency if consideration of collaborative solutions, such as restoration initiatives for habitats or mutually agreeable voluntary solutions, have failed. Regarding water quality, the aim is to keep the list of priority substances that are assessed in the chemical status of water bodies which are in line with the recent scientific and technical expertise. On a concluding note, the Environment Act 2021, focuses on tackling and reducing the issue of sewage discharge, mainly by addressing drainage and sewerage management plans, making water companies collaborate effectively by using a statutory water management plan [26]. Having the process in line with other utility sectors will enhance Ofwat's capability to improve how water companies operate. These measures will ultimately improve the quality of information Ofwat collects for the companies, about their operations and furthermore will update the current process for serving documents under water. The UK state of the water environment for the year of 2019 can be seen in Table 1 (UK, 2021).

Table 1. State of the Water: Water Body Classification in the UK for the year 2019.

	Biology (At a good status)	Physical modification (At a good status)	Water quality (At a good status)	Hazardous substances (At a good status)
Rivers	Fish: 42%; Invertebrates: 76%; Macrophytes and phytobenthos: 45%	Morphology: 49% Flow regime: 88%	Dissolved oxygen: 82% Ammonia: 92% Phosphorus: 45%	Chemical: 0% Chemical status excluding uPBTs: 93%
Lakes	Phytoplankton: 52% Macrophytes and phybenthos: 29%	Morphology: 97%	Total phosphorus: 25% Total nitrogen: 45%	Chemical: 0% Chemical status excluding uPBTs: 100%
Estuaries	Fish: 77% Invertebrates: 67% Saltmarsh: 36% Seagrass: 90%	n/a	Eutrophication: 45%	Chemical: 0% Chemical status excluding uPBTs: 92%
Coastal Waters	Invertebrates: 87% Saltmarsh: 50% Seagrass: 83%	n/a	Eutrophication: 63%	Chemical: 0% Chemical status excluding uPBTs: 100%
Groundwater	n/a	n/a	Quantity: 73% Quality: 45%	Chemical status: 45%
Drinking water	n/a	n/a	Surface water: 52% Groundwater:53%	n/a
Designated Bathing Waters	n/a	n/a	93% at excellent or good status	n/a
Shellfish waters	n/a	n/a	25% passed	n/a

Hot topics in the UK: Current issue

Water pollution has been making big headlines recently. Society needs to be aware of the current issue so it can be tackled properly. In July 2021, the Guardian published a newspaper article revealing the significant impact farming is having on the river Wye in Wales. The article shows how intense and extreme industrial livestock units can be to the health of a water body (Laura De Vito, 2020). The problem begins when chickens are fed with high amounts of soya pellets filled with nitrates and phosphates and distributed in small areas of land. Even after digestion, chicken manure is still filled with nutrients that end up washing to the nearest water body – the river Wye. Once in the river, the excess nutrients cause eutrophication, leading to scarce levels of oxygen in the water, causing stress and killing all the living beings of the river. The lack of regimentation regarding this matter is very harmful to the environment and policies that control the number of animals allowed and a maximum number of farming units permitted per region, should be put in place as soon as possible to avoid more catastrophes like this one (Guardian, 2021). People reacted with shock and anger when on the 13th of January 2022. BBC published an article regarding the poor water quality in the UK's rivers and lakes. Once again, the excessive use of fertilisers and pesticides is mentioned, as well as all the untreated sewage that is deliberately released into rivers, and the "run-off" from roads that contain many different pollutants and oils. The article mentioned the statement from the Environment Agency where it says that people that inhabit a heavily populated and deprived area are more likely to live close to a river classified with a poor chemical/biological status.

It also mentioned that budget cuts to the Environment Agency and Natural Resources Wales over the past few years resulted in a 57% decrease in the number of water quality samples taken every year and that to tackle the issue, the Environment Act 2021 was put in place with a 25-year environmental plan (BBC, 2022).

Another newspaper article published by the Guardian on the 17th of January 2022, argues that leaked documents prove that the Environmental Agency has purposely ignored most high-profile pollution incidents, only addressing 8000 of the 116,000 potential incidents. It also mentions the budget cuts that the agency has faced (reduced by 62% between 2011 and 2016) resulting in massive staff reductions (reduced by a quarter between 2011 and 2016), and its powers weakened [30]. Southern Water, a company responsible for public wastewater collection and treatment that provides water to 2.6m customers and wastewater services to over 4.7m across south east England, made the headlines in July 2021, in an article published by the Guardian, for the worst environmental crime in the past 25 years, by deliberately dumping billions of litres of raw sewage in the protected waters of the sea that bathes north Kent and Hampshire, over the course of several years. This action was done with the sole purpose of avoiding financial penalties and the cost of upgrading sewerage and maintaining infrastructure, stressing the importance of government investment into sewage companies. The crime cost the company £90m in fines, after it pleaded guilty to 51 counts of knowingly dumping into coastal water, toxic, poisonous, polluting and waste matter. The company was able to carry on the crime over so many years by simply underreporting pollution spills, since in 2010 it has been allowed for water companies to self-report pollution incidents (Guardian, 2021). The Guardian published in January 2022 that studies have concluded that chemical pollution is now threatening the stability of global ecosystems since it crossed a planetary boundary. This research took into consideration the rate of production of chemicals that is rapidly rising, and their release into the environment that happens much quicker than the capability of responsible authorities to monitor and investigate the impacts. Once again, experts are saying that stronger regulations are needed, and production and release of chemicals should be monitored as well (Guardian, 2022).

As discussed above, water pollution is one of the main concerns in this technological era we live in and experts from all around the globe work tirelessly daily to find solutions on how to prevent and tackle the issue, ensuring that the quality of the world's most valuable resource is as high as possible. All sorts of water bodies, from oceans to the small-town lake or the water we consume every day must be subjected to strict quality monitoring. Monitoring is done through networks that differ depending on the water body it is prepared to take measurements from and the geographical area it is situated in. Water quality monitoring is important for a variety of reasons, to understand if water is safe for consumption or bathing or if there is an imminent problem that can emerge; it also allows for the understanding of long- or short-term trends and changes that emerge on water bodies, it aids in the design and development of pollution prevention laws and management strategy policies, it allows the relevant authorities to determine who is not complying with the law regarding pollution regulations, and also plays an important role when developing emergency strategies for events like mass erosion, oil spills, radiation leaks etc. Methods used to monitor and model aqueous environments are constantly evolving to address human necessities, traditional methods are of high cost, heavily rely on instant point-in-space measurements, laboratory analysis and physical and computing infrastructure, and are not able to promptly supply with many of the required spatiotemporal features (Linn Persson, 2022). It is clear that in order to improve water monitoring methods, experts should aim to find a way of continuous on-line monitoring using advanced sensor technologies across spatiotemporal resolutions.

Ongoing research has led scientists to believe that a potentially promising alternative for the future of environmental monitoring is the use of low-cost environmental monitoring sensors (LEMS). The end-goal is to reach a network of sensors, where each node has the capacity for online *in-situ* monitoring, physicochemical sensing capacities coupled with machine learning and AI technologies that allow data to be transferred, collected, and analysed by a central location through wireless communication including an early warning system (Theofanis P. Lambrou, 2014; Roy Fisher, 2015). Utilisation of AI to help minimize the sensing "nodes" i.e., learning more from fewer data will help reduce the overall cost/size of sensors in future. These sensor networks have the advantage of being able to continuously monitor aqueous environments for physicochemical parameters, thus contributing to achieving a better representation of long-term trends and modelling (Kevin Murphy, 2015). Moreover, the sensors' low cost together with the relatively small dimensions and light weight contribute to making them easier to deploy, allowing for extensive, distributed networks to be put in place, increasing spatial coverage of monitoring (Stefan Krause, 2015; Li, 2021; Karimi-Maleh, 2019; Nickels, 2012; Kumari, 2021; Gennarelli, 2013; Sohrabi, 2021). Also, it is important to mention that because they are compact, low-cost (Anastasova, 2012; Radu, 2010), and easy to use, these sensors can be deployed in developing countries and heavily polluted areas without the need for an expert to use the machinery. Some examples of LEMS that are currently being manufactured in the

UK are depicted in Table 2, Table 3, and Table 4.

Table 2. Example of LEMS manufactured in the UK.

Water sensors											
Company(Based in)	Water sensors	Picture	Cost	Portable	Dimentions (mm)	weight	Used by non-professional?	Expected lifespan	Indoor/outdoor measurements	Parameters	Technical specifications link
ATI (UK)	Q46D		1452£	No	61 x 140	8.1kg	No	10 years	outdoor	Dissolved Oxygen	http://www.atiuk.com/UserFiles/private/Product%20Brochures%20-%20Water/L-Q45D-ODO.pdf
ATI (UK)	Q46N		5229£	No	386 x 335 x 180	7.7kg	No	5 to 6 years	Outdoor/indoor	Ammonia and monochloramine	http://www.atiuk.com/UserFiles/private/Product%20Brochures%20-%20Water/L-Q45N.pdf
Watr (UK)	Watr		2620 £	Yes	442.4 x 258 x 352.4	1kg	Yes	n/a	outdoor	Salinity, Ammonia, Metals, BOD, Sulfide, Rhodamine, COD, Sulfite, Crude Oil, Turbidity, Nitrates, Algea, TDS, ORP, Phenol	https://www.watr.tech/technical-specification-sept-2021.pdf
rshydro (UK)	Orion star A329		1790£	Yes	60 x 105 x 240	0.450kg	No	10 years	Outdoor/indoor	pH, ion concentration, mV, ORP, conductivity,TDS, salinity, dissolved oxygen	https://www.rshydro.co.uk/files/A329_multi_parameter_portable_meter_specification.pdf
Bell environmental (UK)	Aquaread AP-2000		2860£	Yes	290 x 42	0.700kg	Yes	10 years, although sensing elements might need to be changed after 1 or 2 years	Outdoor/indoor	pH; ORP; Conductivity; TDS; SSG; Resistivity; Salinity; Dissolved oxygen; temperature	https://www.aquaread.com/downloads/data-sheets/AP-20002000-D%20Data%20Sheet.pdf
Palintest (UK)	Multiparameter Pocket Sensor		215,10£	Yes	n/a	0.200kg	Yes	n/a	Outdoor/indoor	pH, ORP, conductivity, TDS, salinity, temperatue	file:///C:/Users/marta.jesus/Downloads/Pocket-Meters-pH-Conductivity-TDS-and-Multiparameter.pdf

Table 3. Sensors and hidden costs

Company	Sensor name	Sensor type	Hidden Cost
ATI	Q46D	Water	Training can be provided for non-professionals = 595£, Reagents for calibrations= 3x 79£, DO sensor electrolyte 20£, membranes= 16.60£
ATI	Q46N	Water	
Watr	Watr	Water	n/a
RsHydro	Orion Star A329	Water	Calibration services= 187,02£ + Buffer pack= 30£
Bell Environmental	Aquaread AP-2000	Water	Calibration fluid
Palintest	Multiple Pocket Sensor	Water	Calibration solution = 46,20£ Delivery= 14£
Tera	Tera	Soil	n/a

Table 4. LEMS characteristics

Sensor	Gas	Particle	Other	Type	Units	Range	LOD	Precision	Accuracy
AQMesh	NO			Electrochemical	ppb	0-20 000 ppb	<1 ppb	>0.9	1ppb
	NO2			Electrochemical	ppb	0-20 000 ppb	<1ppb	>0.85	4 ppb
	NOx			Electrochemical	ppb	0-40 000 ppb	<2 ppb	>0.9	4 ppb
	O3			Electrochemical	ppb	0-20 000 ppb	<1 ppb	>0.9	5 ppb
	CO			Electrochemical	ppb	0-1 000 000 ppb	<30 ppb	>0.8	20 ppb
	SO2			Electrochemical	ppb	0-100 000 ppb	<2 ppb	>0.7	20 ppb
	H2S			Electrochemical	ppb	0-100 000ppb	<1 ppb	>0.7	1 ppb
	TVOC			Electrochemical	ppm	0-2.5 ppm	<0.1 ppm	>0.95	0.05 ppm
	CO2			Electrochemical	ppm	0-5 000 ppm	<1 ppm	>0.9	30 ppm
		PM1		Optical Particle counter	$\mu g/m^3$	0-100 000$\mu g/m^3$	0$\mu g/m^3$	>0.9	5$\mu g/m^3$
		PM2.5		Optical Particle counter	$\mu g/m^3$	0-150 000$\mu g/m^3$	0$\mu g/m^3$	>0.9	5$\mu g/m^3$
		PM4		Optical Particle counter	$\mu g/m^3$	0-250 000$\mu g/m^3$	0$\mu g/m^3$	>0.9	5$\mu g/m^3$
		PM10		Optical Particle counter	$\mu g/m^3$	0-250 000$\mu g/m^3$	0$\mu g/m^3$	>0.85	5$\mu g/m^3$
		PM_Total		Optical Particle counter	$\mu g/m^3$	0-350 000$\mu g/m^3$	0$\mu g/m^3$	>0.85	5$\mu g/m^3$
			POD Temperature	Solid state	°C or °F	-20°C to 100°C	0.1°C	>0.9	2°C
			Pressure	Solid state	mb	500 to 1500 mb	1 mb	>0.9	5 mb
			Humidity	Solid state	%	0 to 100%	1% RH	>0.9	5% RH
			Noise	Omnidirectional mic	dB	35 to 100 dB SPL	20 Hz – 20 kHz	>0.8	1 dB
Sensor	**Gas**	**Particle**	**Other**	**Type**	**Units**	**Range**	**LOD**	**Precision**	**Accuracy**
Awair	CO2				ppm	400-5000 ppm			
		PM2.5			µg/m3	0-1000 µg/m3			
			TVOC		ppb	20-60000 ppb			
			Temperature		°C or °F	0°C to -90°C			
			Humidity		%	0 to 100%			
			Light		lux	0 to 64000 lux			
			Noise		dBa	48 to 90 dBa			
			Awair Score		n/a	0 to 100			
Sensor	**Gas**	**Particle**	**Other**	**Type**	**Units**	**Range**	**LOD**	**Precision**	**Accuracy**
FGSD	Methane			Catalytic		100% LEL			
	Hydrogen			Catalytic		100% LEL			
	Propane			Catalytic		100% LEL			
	Acetylene			Catalytic		100% LEL			
	Carbon Monoxide			Electrochemical		300 ppm			
	Nitrogen Dioxide			Electrochemical		10.0ppm			
	Oxygen			Fluorescent		25.00%			
	Methane			Infra-red		100% LEL			
	Carbon Dioxide			Infra-red		5.00%			
	Propane			Infra-red		100% LEL			
	Ethylene			Infra-red		100% LEL			
	Sulphur Hexafluoride			Infra-red		2000ppm			
	Chlorine			Electrochemical		5.00ppm			
	Hydrogen			Electrochemical		2000ppm			
	Nitric Oxide			Electrochemical		100ppm			
	Sulphur Dioxide			Electrochemical		20.0ppm			
	Ammonia			Electrochemical		100ppm			
Sensor	**Gas**	**Particle**	**Other**	**Type**	**Units**	**Range**	**LOD**	**Precision**	**Accuracy**
OPC-N3		PM1		Optical Particle counter	$\mu g/m^3$	0.35 to 40 µm spherical diameter			
		PM2.5		Optical Particle counter	$\mu g/m^3$				
		PM4.25		Optical Particle counter	$\mu g/m^3$				
		PM10		Optical Particle counter	$\mu g/m^3$				
Sensor	**Gas**	**Particle**	**Other**	**Type**	**Units**	**Range**	**LOD**	**Precision**	**Accuracy**
VOC-A4	VOC			Electrochemial	ppm	1 to 100 ppm	10 to 50 ppb		

Although sensor technology has advanced significantly in recent years, there are still gaps when it comes to low-cost environmental monitoring sensors. Challenges include: a short lifespan of hardware resulting in a short working time of the sensor, high need for maintenance (including calibrations, battery replacements, etc). Also, even though the sensors are manufactured with inexpensive materials, often the monitoring destination requires environmental robustness that could potentially increase costs, adding hidden costs that render them expensive after all. Moreover, the large amount of raw data extracted can be a challenge to analyse and interpret, adding another potential hidden cost that could make the sensor more expensive (Feng Mao, 2018).

The UK is contributing to the latest research: the University of York is being supported by the Engineering and Physical Sciences Research Council (EPSRC) to develop a water monitoring sensor able to detect microorganisms responsible for diarrhoeal life-threatening diseases in South Pacific islands (York, 2019). AquAffirm is developing a next-generation sensor capable of detecting and mapping the chemical arsenic in water, a debilitating naturally occurring chemical that is present all over the globe but endemically contaminates south Asian drinking-waters . ANB Sensors Ltd is being funded by the Natural Environment Research Council (NERC) to develop a prototype of a pH sensor that is able to self-calibrate to deploy to aquaculture and hydrophobic industries (Aquafirm Ltd, 2022). In 2019, Cornell University funded by NERC studied the possibility of a low-cost sensor to measure levels of lead in drinking water using complementary metal oxide, semiconductor sensors, they plan on transferring to commercial silicon sensors, and results show that the sensor detects gamma radiation from about 10 to 100keV for less than 1.4 hours of measurement (Deisting, 2020). In 2021, a partnership between the University of Cardiff, the University of Bristol, and the Westcountry Rivers Trust, funded by the Engineering and Physical Sciences Research (EPSRC), aimed to develop a prototype of a low-cost wireless sensor with a base station, designed specially to be used by citizen scientists (with the right amount of training and support). The sensor called Hydrobean measures electrical conductivity, temperature, and pressure which are parameters that can be good indicators for water quality. The prototype was tested during 5 days in a Welsh stream having the predicted results for trends in EC and stage data; however, the sensor batteries had to be replaced every day which influenced the results . Scientists are investigating the spread of antimicrobial resistance in waterways, as published by University of Birmingham in August 2020. Experts from this university together with a team of the Indian Institute of Technology (IIT) are working on a project called AMRflows. The project consists in field sampling and mathematical modelling of two Indian rivers, the Musi river and the Adyar river, with the final aim of predicting and understanding how far resistant bacteria can travel before it dies or is eaten, how antibiotics flow through a river and how far they get carried away, aiding in the study of antimicrobial resistance (AMR) spread in a quantitative and predictive manner. Once scientists can have this quantitative risk assessment, it will be possible to create environmental standards for the safe concentration of antibiotics in water bodies.

Groundwater can contain a wide range of components, including those that are naturally occurring and those that come from a human source; some of these have the potential to harm the environment or human health. Regulations set limits for certain parameters. The term ’emerging contaminant’ is used to describe a substance that is not yet regulated but may be of environmental or human health concern (Gaston, 2019; Ascott, 2016; Lapworth, 2018; Lapworth, 2015; Lapworth, 2012; Manamsa, 2016; Manamsa, 2016; Stuart, 2012; White, 2016; White, 2019; Stuart, 2014).

Synonyms include ‘substances of emerging concern’. Some of the new early-stage development includes capacitive touchscreen sensing – a measure of electrolyte conductivity which would enable accessible, rapid measurements and would open a huge range of applications. The authors claim that one of the possible application areas would be the detection of arsenic contamination in drinking water (Horstmann et al., 2021).

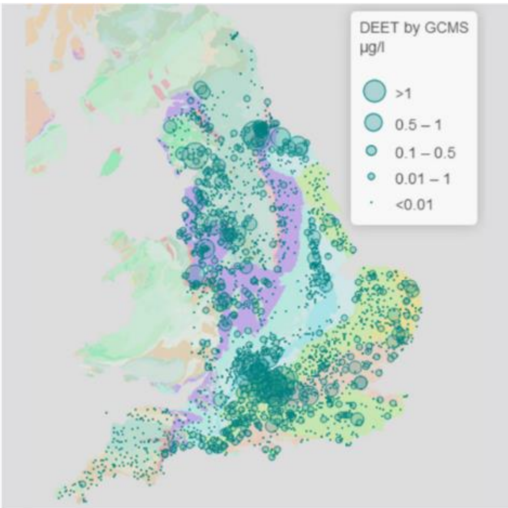
One of the future aims is to develop an innovative integrated framework to map groundwater vulnerability in a fine temporal scale by applying an integrated AI, GIS, remote sensing and statistical downscaling methods; this will involve usage of low-cost water quality sensors to collect fine temporal-scale groundwater quality datasets.

The monitoring of water and air quality is important. Colourimetric sensors deliver quick, naked-eye detection, low-cost, and adequate determination of environmental analytes. Disposable sensors are cheap and easy-to-use devices for single-shot measurements. Due to increasing requests for *in situ* analysis or resource-limited zones, disposable sensors' development has increased. This review provides a brief insight into low-cost and disposable colourimetric sensors currently used for environmental analysis. The advantages and disadvantages of different colourimetric devices for environmental analysis are discussed (Alberti et al., 2020).

Digital mapping of pollution

https://www.bgs.ac.uk/geology-projects/emerging-contaminants-in-groundwater/ Emerging contaminants found in English groundwater include the medicines iboprufen (painkiller and anti-inflammatory) and carbamazepine (used to treat epilepsy).

Microorganism contaminants in groundwater in England. Screening programmes are employed by the Environment Agency (EA) to look at a wide range of compounds including many that are not currently regulated.



N,N-diethyl-m-toluamide (DEET) by GCMS across England. © BGS/UKRI incorporating Environment Agency data.

The insect repellent DEET was the seventh most frequently detected compound (by gas chromatography mass spectrometry (GCMS) screen), being detected in over five per cent of samples. Pharmaceuticals such as carbamazepine and clopidol were detected in over a third of samples analysed by liquid chromatography mass spectrometry (LCMS) screen.

https://environment.data.gov.uk/water-quality/view/landing - The Water Quality Archive provides data on water quality measurements. Samples are taken at sampling points around England and can be from coastal or estuarine waters, rivers, lakes, ponds, canals or groundwaters. They are taken for a number of purposes including compliance assessment against discharge permits, investigation of pollution incidents or environmental monitoring. The archive provides data on measurements and samples dating from 2000.

https://www.sas.org.uk/map/ Safer seas service interactive map; at SAS the voice of ocean is heard by Parliaments and governments of the UK.

The UK ranks just 25th out of 30 European countries for Bathing Water quality

(European Environment Agency, 2019)

There are 21,462 licensed sewer overflows across England and Wales, 89% of which discharge into rivers

(Environment Agency, 2020) and (WWF, 2019)

Only 14% of British rivers meet good environmental standards

(European Commission, 2000)

Projected population figures suggest a 44% increase in sewage load in England and Wales between 1961 to 2039, equivalent to an extra 3 billion litres per day

(WWF, 2019)

Research by the European Centre for Environment and Human Health (ECEHH) found that bathers in the UK remain just as likely to become ill from seawater as they were in the 1990s

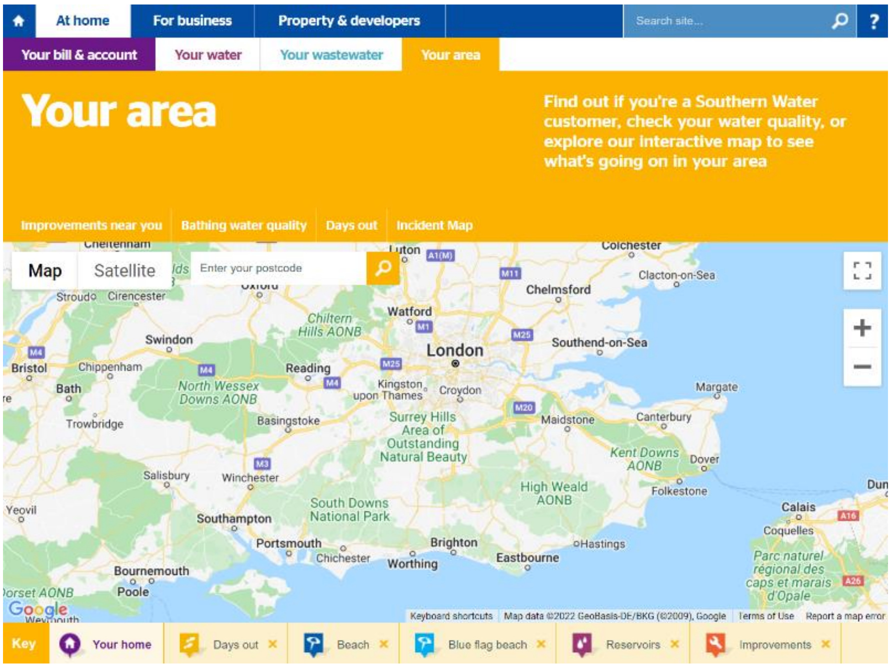
(Leonard, A.F.C., R. Garside., O.C. Ukoumunne & W.H. Gaze, 2020)

If no action is taken on antimicrobial resistance then by 2050, an estimated 10 million antimicrobial resistant bacteria related deaths will occur every year

(Dame Sally Davies, UK Special Envoy for Antimicrobial Resistance on BBC Radio 4's "Costing the Earth" programme 2020)

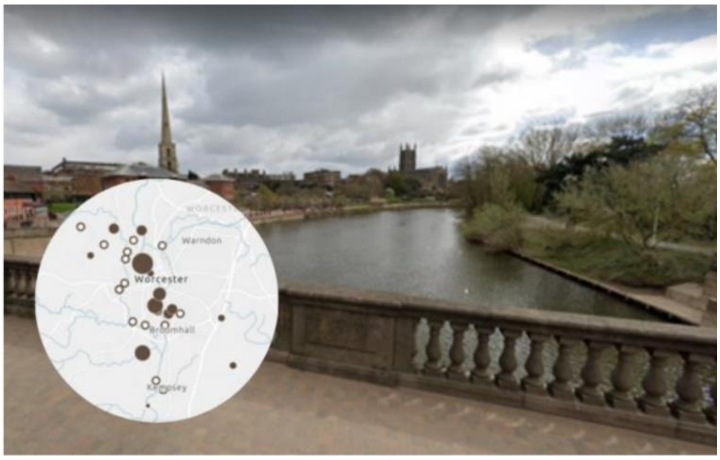
https://environment.data.gov.uk/bwq/profiles/ Bathing water quality interactive map; Swimfo allows user to look up details of a designated bathing water by name or location. Water quality at designated bathing water sites in England is assessed by the Environment Agency. From May to September, weekly assessments measure current water quality, and at a number of sites, daily pollution risk forecasts are issued. Annual ratings classify each site as excellent, good, sufficient, or poor based on measurements taken over a period of up to four years.

https://www.southernwater.co.uk/your-area Interactive map shows the South Coast with icons indicating all the sampled beaches *https://www.wwf.org.uk/uk-rivers-map* UK rivers map

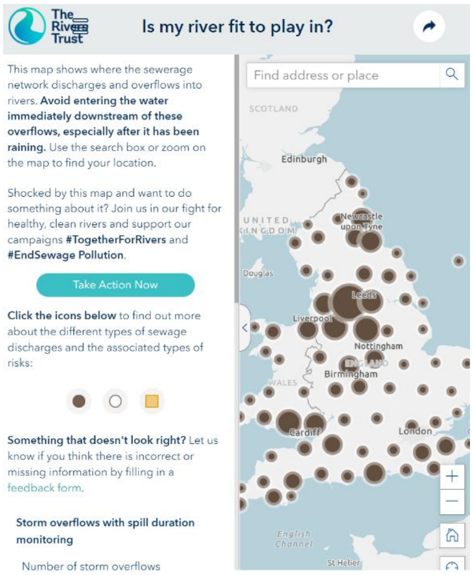


This map will help user find out about a local river and its condition.

https://www.worcesternews.co.uk/news/19676954.map-shows-raw-sewage-emptied-worcestershire-rivers/ - Map shows raw sewage emptied into Worcestershire. An interactive map shows how sewage is being emptied into rivers and bathing water in the UK - including in Worcestershire. Data released by the Rivers Trust has shown that Severn Trent Water discharged raw sewage for over 550,000 hours in 2020.



New map shows raw sewage is being emptied into rivers across Worcestershire.



Gaps identified

1. A key gap remains the short lifespan of much low-cost environmental sensor hardware; the short operational life of the sensor and increased need for maintenance (including calibrations, battery replacements, etc) lead to higher operational costs over the lifetime of the sensor which can make them commercially undesirable.
2. Despite the fact that sensors are manufactured with inexpensive materials, often the monitoring destination requires environmental robustness that often increases costs.
3. Need/opportunity to combine computational methods like AI and big data with low-cost sensors to get best value and impact from the data.
4. Networking of sensors and use of Artificial Intelligence (AI) tools and algorithms for environmental decision-making and policymaking for different stakeholders and at different scales.

Conclusion

On a concluding note, as mentioned earlier the consequences of water pollution can be devastating. It is extremely important to advocate and educate society on this topic to prevent further damage and demand better laws and law enforcement on water protection. Low-cost environmental monitoring sensors are a novel way of monitoring water bodies, and once mastered will provide the scientific community with valuable information on water pollution and lead researchers to what needs to be done next. As previously mentioned, the UK is contributing to the latest research with several different projects developing biosensors and chemical sensors. The research on these types of sensors is also aiming to have products to be used by citizen scientists allowing the scientific community to obtain a larger amount of data by educating the citizens on the topic and creating advocacy.

India

Environmental pollution has risen to become a major issue of concern in the 21st century and which cannot be overlooked by any means. Human activities have helped accelerate the discharge of organic and inorganic pollutants in the environment, especially environmental waterbodies. The major problem with such pollutants is that they are not readily biodegradable, and hence they tend to accumulate in the water bodies and the food chain utilising bioaccumulation inside different aquatic creatures. Heavy metals are generally defined as metals or metalloids having relative density, from 3.5 to 7. Heavy metals are considered the causes of significant pollution due to their toxicity, ability to bioaccumulate and cause adverse effects on the aquatic ecosystem over the long term (Bahadir, 2007).

Pollutants of concern

Mining

The mining industry is one of the significant contributors to the heavy metal pollutants in environmental water bodies. Extraction of ores from mines and smelting, processing, and refining of the ores releases different heavy metal pollutants like cadmium (Cd), arsenic (As), lead (Pb), zinc (Zn), copper (Cu) into the drainage. The acid mine discharge from both the active and abandoned mines adds many pollutants to the surface and groundwater.

Domestic Discharge

Domestic water discharge contains various trace metals thanks to various waste metallic products, detergent and other household drainages, corrosion in pipes. All these discharge results in the addition of Cu, Zn, Ag, Cd, Cr, Fe etc. in the local water bodies.

Industrial Wastewater and Discharge

Industrial wastewater and untreated discharge are significant metallic pollutants to local aquatic bodies. The character of the pollutant depends on the type of industry.

The sources of different major heavy metal pollutants with their limit in drinking water by the Bureau of Indian Standard (BIS) and World Health Organisation (WHO) has been presented in Table 5 (Govt. of India, August 2019).

Table 5. Major heavy metal pollutants with their limit in drinking water

Sl. no.	Pollutant	Major Sources	BIS limit in drinking water (mg/l)	WHO Limit (mg/l)
1	Arsenic	Arsenic containing fungicides, pesticides and herbicides, metal smelters, byproducts of mining activities, chemical wastes	0.01	0.01
2	Cadmium	Cadmium producing industries, electroplating, welding. Byproducts from refining of Pb, Zn and Cu, fertilizer industry, pesticide manufacturers, cadmium–nickel batteries, nuclear fission plants	0.003	0.005
3	Chromium	Metallurgical and chemical industries, processes using chromate compounds, cement and asbestos units	0.05	0.1
4	Lead	Automobile emissions, lead smelters, burning of coal and oil, lead arsenate pesticides, smoking, mining and plumbing	0.01	0.01
5	Mercury	Mining and refining of mercury, organic mercurial's used in pesticides, laboratories using mercury	0.001	0.001
6	Fluoride	Industrialization, motorization, fluoride containing pesticides, fluoridation of drinking water supplies, dental products, refrigerants, and fire extinguishers	1.0	1.5

Agricultural (Agrochemical) waste:

Agrochemicals (fertilizers and pesticides) have become an integral part of modern agriculture as these are required for increasing yields with relatively less effort. The exponential growth of the population has compelled the use of agrochemicals to improve the productivity of food grains to meet its food demand. The consumption of agrochemicals in India (2019-2020) is portrayed in Table 6.

Table 6. Consumption of Agrochemicals in India (2019-2020)

Agrochemicals	Units	Values
Fertilizers (Nitrogen+ Phosphorus)	Lakh tonnes	293.69
Pesticides	Thousand tonnes	61.7

However, prolonged application of agrochemicals (both fertilizers and pesticides) can ultimately lead to soil health deterioration and environmental pollution, especially soil and water (Figure 3). Several researchers have reported the risks associated due to abuse of agrochemicals to the environmental systems.

It is estimated that around 6 million tons of fertilizers and 9000 tons of pesticides enter the river system each year. More than 90% of water and fresh samples from all streams sampled often contained one or more pesticides. Pesticides contamination of groundwater is of vital concern for the people of India, especially in those areas where the primary source of drinking water is groundwater aquifers. Analysis of drinking water samples from across India showed the presence of HCHs and endosulfan isomers and DTT metabolites in high concentrations. Therefore, detection of these toxic residues and subsequent elimination of these ill-fated substances from the environment is the need of an hour. An overview of the pesticides and their safe value is tabulated in Table 7

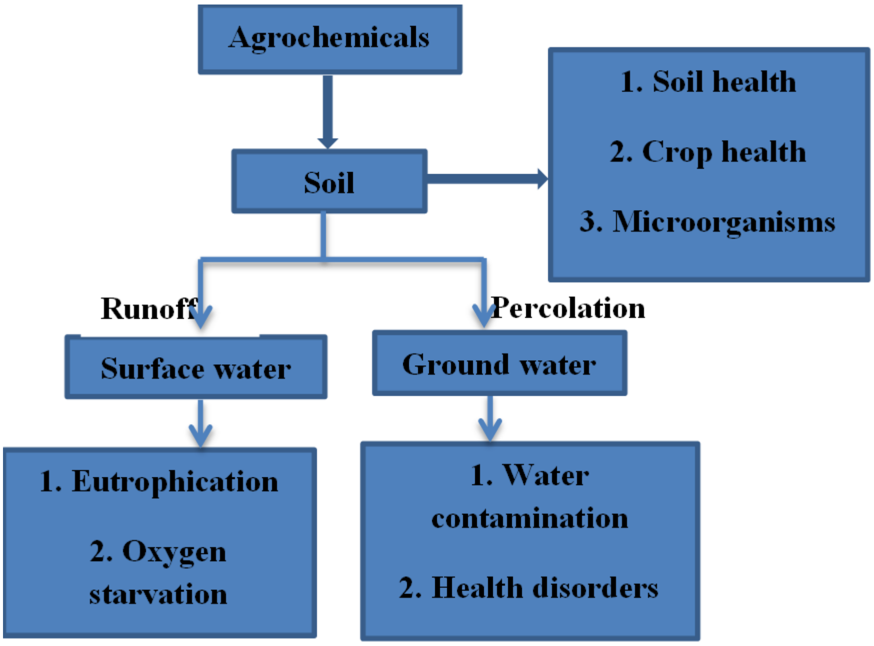


Figure 3. Negative impacts of agrochemicals

Table 7. Guideline values of pesticide levels in drinking water

Pesticide	Guideline Value (µg/L)	Pesticide	Guideline Value (µg/L)
Alachlor	20	Metolachlor	10
Aldicarb	10	Molinate	6
Atrazine	2	PentaChlorophenol	9
Bentazone	300	Permetherin	20
Carbofuran	7	Propanil	20
Chlordane	0.2	Pyridate	100
DDT	2	Simazine	2
Hexachlorobenzene	1	2,4,5-T	9
Isoproturon	9	Terbuthylazine	7
Lindane	2	Trifluralin	20

The excessive use of these pesticides and fertilizers has targeted other living creatures (e.g., fishes, birds, and humans) as well, in addition to pests/insects. Apart from soil health, naturally available biological organisms for pest control, adjoining vegetation and chronic effects on human health were observed due to pesticides in environmental systems. Common human health disorders are immune system problems, hormonal problems, delusion, reproductive problems, and even cancer. According to the researchers, the extent of human health problems due to pesticide poisoning can be categorized into mild or moderate (e.g., headache, dizziness, gastric problems, lack of sensation, weakness, hyperirritability, flu, itchiness of the skin, unclear vision, and neurological problems) and severe (e.g., paralysis, loss of sight), and sometimes death (Zhou, 2022).

Sensor based techniques for Water Quality Monitoring - Indigenous R&D

Some of the indigenous research in different universities for chemical and agricultural waste in water quality sensing has been tabulated in Table 8 and Table 9.

More details on the sensors are available in Annex II.

Table 8. Indigenous R&D in chemical water quality sensors

Parameter	Sensing technique	Chemistry	TRL	LOD	Dynamic range	Reference
Cadmium	Fluorescence spectroscopy	TG-CdSe QD-Cd^{2+}	4	0.32 µM	1.0 to 22 µM	(Brahim, 2015)
	UV-Visible spectroscopy	Mesoporous silica-TPDP	4	2.93 nM	17.792 µM to 642.2 µM	(Awual, 2018)
	Immunochromatographic strip	AuNP- monoclonal antibody anti- Cd(II)-ITCBE (3A9)-Cd^{2+}	4	1.77 nM	1.77 nM to 88.9 nM	(Song, 2018)
	UV- Visible spectroscopy	CSDTC-Cd^{2+}	4	63 nM	50 to 500 µM	(Mehta, 2015)
	Colourimetric	Au-Ag NPs-Cd^{2+}	5	44 nM	0.4 to 38.6 µM	(] Du, 2018)
	Colourimetric	DL-G-CA-Au-Cd^{2+}	5	21 nM	0.05 to 500 µM	(Yadav, 2018)
	GCE	MOF-Cd^{2+}	5	1.06 nM	0 to 60 µM	(Li, 2019)
	Electrochemical	Zirconia MOF-CNT-Cd^{2+}	4	1.77 nM	4.4 nM to 1.5 µM	(Wang, 2021)
Chromium	Colourimetric	PVP) capped AgNPs-Cr^{6+}	5	34 nM	100 nM to 2.4 µM	(He, 2019)
	Colourimetric-Smartphone	AuNP+MA-Cr^{6+}	5	1.9 nM	3.8 nM to 38.4 nM	(Moham d, 2021)
Mercury	Tyndall effect-based assay	AgNPs capped with L-tyrosine-Hg^{2+}	5	0.85 nM	5 nM to 4 µM	(Huang, 2021)
	Optical (Fluorescence)chemosensor	DTD+ PVC+DOP-THF-Hg^{2+}	4	2.4 nM	Up to 100 nM	(Ali, 2021)
	Colourimetric	Ag NPs	4	1.25 µM	Up to 100 µM	(Aminu, 2021)
	eFBG	CNC-Hg2+	5	1 pM	1 pM to 1 µM	(Kavitha, 2021)
	Electrochemical	AuNP- aptamer-Hg^{2+}	5	0.33 fM	1 fM to 1 µM	(Xie, 2021)
	Photo - electrochemical	Ag@Ag_2S-Hg^{2+}	5	0.5 pM	0.0010 to 5.0 nM	(Zhang, 2021)
Fluoride	Colourimetric	MPBA –AuNPs-F^-	5	0.345 µM	10 – 30 µM	(Wu, 2019)
	Colourimetric	AgNPs-F^-	5	0.2	1µM to 10 µM	(Motahhari, 2021)
Lead	Coloirimetric assay	SiO_2 NPs-Pb^{2+}	5	2.5 nM	10 to 200 nM	(Duan, 2022)
	Plasmonic colourimetric	AgNP	5	38.61 nM	96.53 nM to 4.8 µM	(Shrivas, 2019)
	Electrochemical	Au-screen-printed electrode	7	72.4 nM	72.4 nM to 1.4 µM	(Bernalte, 2020)
	Electrochemical	AuND@GPL	5	0.9 nM	4.8 nM to 241.3 nM	(Giao, 2019)
	SPR	Chitosan-glutathione-Pb^{2+}	4	6.2 nM	4.8 nM to 33.7 nM	(Boruah, 2018)
	eFBG	AuNP-MA+Pb^{2+}	5	10 fM	10 fM to 100 nM	(Vajresh K. N., 2022)
Arsenic	Colourimetric	Glucose-AuNPs- As^{3+}	4	7 nM	13.3 nM to 186.8 nM	(Boruah, 2019)
	Fuorescence	CDN/Ce's-aptamer- As^{3+}	4	2.6 nM	6.6 nM to 77.4 nM	(Zhang, 2019e)
	Fluorescence	Eu: Y2O3 nano phosphor-PVA- As^{3+}	5	0.7 nM	0.7 nM to 1.3 µM	(Dwivedi, 2022)
	Electrochemical	Ag-AuNPs modified GCE - As^{3+}	5	0.00004 nM	0.13 nM to 133.4 nM	(Yadav R, 2020)
	Optical	Liquid crystal-based aptamer-As^{3+}	5	50 nM	50 to 1000 nM	(Nguyen, 2020)

Table 9. Indigenous R&D in agrochemical sensors

Parameter	Sensing technique	Chemistry	Detectin limit(μM)	Dynamic range (μM)	TRL	Key findings	Ref
Nitrate	Potentiometric	Co(II)-composed PVC membrane	3.98	$10\text{-}10^5$	5	Tested for tap, mineral and river water	(Pietrzak, 2020)
	Optical	Fiber optic SPR probe Cu-NPs/CNT	NA	2.5 to 10^3	4	Simple structure Suitable for remote multiparameter measurement	(Sterzi, 2019)
	Optical	Optical microfiber	2.74	0 to 19 $X10^3$	4	Tested for sea water Suitable for in situ detection Easy to construct and cheap	(Yang, 2020)
	Optical	Deep UV LED detector	0.64	1.6 to $1.2X10^3$		Tested for tank water , waste water and fresh water Suitable for in situ detection Inexpensive	(Murray, 2020)
Phosphate	Potentiometric	NiO/NiOOH-PrC electrode	1	1 to 105		High sensitivity, durability and reusability Inexpensive Rapid on-site analysis	(Sedaghat, 2019)
	Potentiometric	Al2O3-rGO	0.105	263 to 1.05		Tested for waste water Inexpensive and miniaturized sensor Suitable for real time detection	(Zhou, 2020)
	Optical	Ceteareth 25 -AgNps	0.076	2 to 240		Tested for drinking water	(Salem, 2021)
	Optical	Tb-MOF-Zn	$4X10^{-3}$	0.01 to 200		High selectivity towards PO_4^{3-}	(Fan, 2020)
Ammonia	Potentiometric	PpyCOSANE-Au	40	N/A		Tested for tap water and sewage Integrated to passive lab on chip system	(Gallardo-Gonzalez, 2019)

						Suitable for real time analysis	
	Optical	BP flower extract paper	118	294 to 2941		Green and inexpensive	(Jaikang, 2020)
	Optical	MB@AuNP	24	57.7 to 769		Smartphone based detection	(Keskin, 2020)

Commercially available sensors

University level prototypes for pilot study

Many universities across India have been working to produce low-cost sensors with collaborations with foreign universities, companies, or funding agencies. Some of their research has been deployed in various regions for pilot studies to collect data and validate the sensor result with standard methods. Some of these sensors have been tabulated in Table 10.

Table 10. University/company/funding agencies collaboration sensors for water quality

Company	Sensor	Picture	Cost	Portable	TRL level	Advantage	In field	Parameters	Technical specification link
IIT, Madras ,DST and UK	Colorimetric paper-based microfluidics		NA	Yes	7	• Simple • Low-cost • Highly sensitive • Rapid • No sophisticated instrument • No trained personnel	Yes	Antimicrobes triggering pollutants	https://www.biospectrumindia.com/news/58/18566/iit-m-uk-researchers-develop-paper-based-sensor-to-detect-antimicrobial pollutants.html
IIT, Bombay and Industry partner from Japan	Polysensor		NA	Yes	7	• Simple • Low-cost • Highly sensitive	Yes	pH, Chloride, Nitrate, EC, Salinity, TDS	https://www.ircc.iitb.ac.in/IRCC-Webpage/PDF/update/Issue1_2007/water-quality-monitoring.html
IIT Kanpur, start-up Earth Analytics Analytics Pvt Ltd and Kratsnam Technologies Pvt Ltd	Colourimetric test-strip based on smartphone technology		NA	Yes	7	•	Yes	Multiple parameters	https://www.iitk.ac.in/new/incubated-start-ups-developed-padmavati

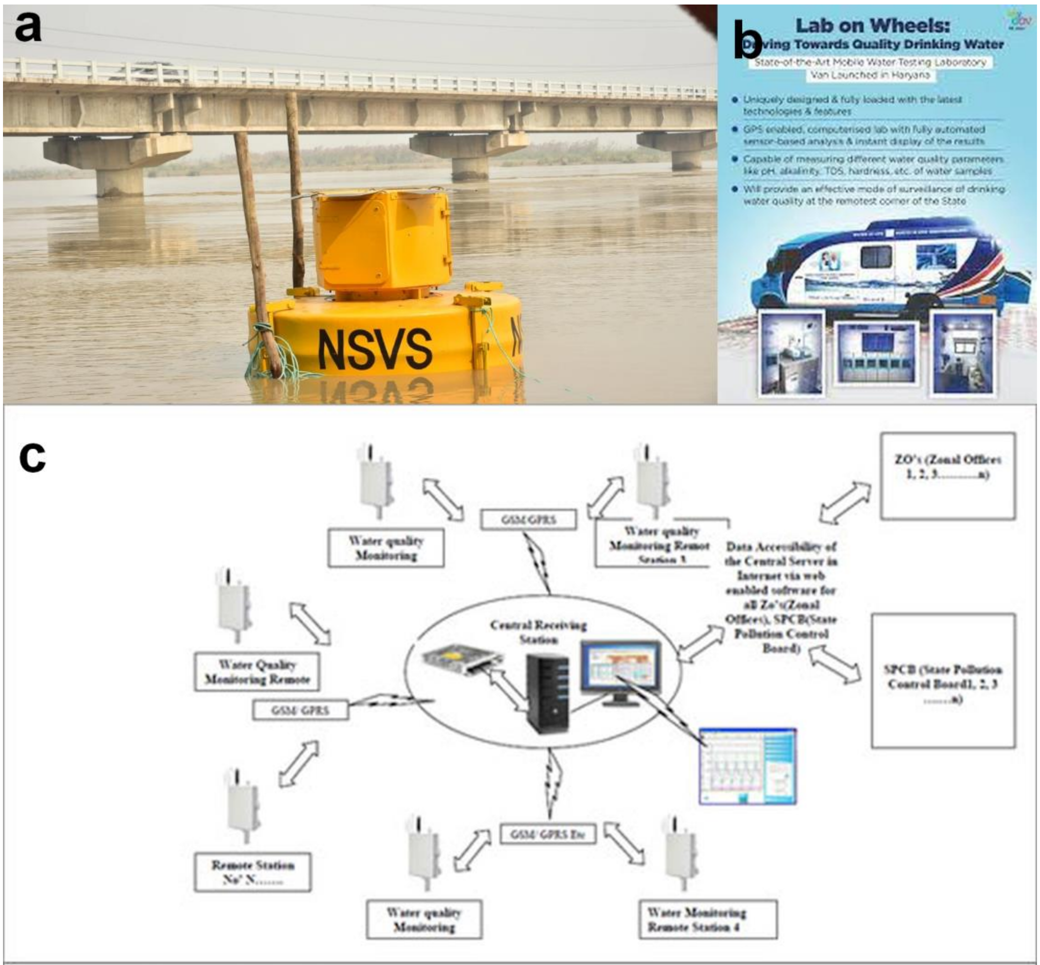
Commercial water quality collaboration sensors

The University/company/funding agencies' collaboration sensors have been mass-produced and are replacing the standard expensive ones to give better control over the water quality. These sensors are tabulated in Table 11.

Table 11. Commercial level sensors developed by universities/ company/funding agencies' across India

Company	Sensor	Name of the system	Cost	Portable	Advantage	In field	Parameters	Technical specification link
Indian Institute of TechnologyKanpur (IIT-K)-NSVS	Web-based system	Fig. 4a NSVS Web-based system	Low cost	Yes	• Array of sensors • Autosamplers Semi-submersible, All-weather, Robust, • Stable	Yes	pH, conductivity, dissolved O_2, total dissolved solids, specific gravity, metallic ions in water	Indian Unveils Web-Based Water Quality Monitoring System for River Ganges – OpenGov Asia
Department of Drinking Water & Sanitation, National, Jal Jeevan Mission	Haryana's mobile laboratory	Fig 4b Haryana's mobile laboratory	₹ 99 lakh	Yes	• GPS enabled • On-site recording and reporting of results through a smart phone • Fully automated sensor-based analysis • semi-automated analysis by spectrophotometer		pH , TDS, Turbidity, Chloride (As Cl), Total Alkalinity as Calcium Carbonate, Total Hardness (as $CaCO_3$), Sulphate (as SO_4), Iron , Total As, F, NO_3, Total coliform bacteria, E.coli/ Thermotolerant coliform bacteria, Free residual Chlorine , Colour, Odour	WQMS Framework.cdr (jalshakti-ddws.gov.in)
CPCB's Real time water quality monitoring	1.UV Spectrometry 2. Optical sensors 3. multi parameter electrode 4.Amperometric membrane	Fig. 4c CPCB's Real time water quality	₹ 35-40 lakhs	Yes	• Operational in real time mode • Tolerant to extreme environmental conditions • Low maintenance	Yes	1. SS, COD, BOD, TOC, Nitrate, Colour and Turbidity 2. Dissolved oxygen & temperature 3. pH, Conductivity, Salinity and Temperature 4. free chlorine (Cl_2 + HOCl + OCl^-) or total chlorine (free chlorine + combined chlorine)	CPCB's Real time water quality monitoring (cseindia.org)

NSVS- Niracara Svayamsasita Vedh Shala
CPCB - Central Pollution Control Board



Source: Central Pollution Control Board

Figure 4. (a)NSVS Web-based system (b)Haryana's mobile laboratory (c) CPCB's Real time water quality monitoring

Recent advances in sensing techniques

Many government organisations are working towards the improvement of water quality. Some of the most important are the Department of Science and Technology (DST), The Asian and Pacific Centre for Transfer of Technology (APCTT). Some of the projects that they have initiated are explained in this section.

Water Technology Initiative, initiated in August 2007, aims to promote R&D activities to provide safe drinking water at affordable cost and in adequate quantity using appropriate Science and Technology interventions evolved through indigenous efforts. Since quality is the primary consideration of safe drinking water, processes that imply nano-material and filtration technologies have been focused on. The initiative also includes the pilot testing of a credible number of products and referencing selected technologies to the social context of the application region. Many initiatives such as Technological solutions to address multiple local water challenges, Drinking and wastewater treatment, Filter technology for Domestic and Community use, rainwater harvesting, groundwater recharge are some schemes funded by DST for water quality improvement. They have supported and promoted monitoring and reuse technologies at the lab scale and pilot level. Different academic institutions/organisations have been working in this domain intensively. An extract of the same has been illustrated in Table 12.

Table 12. Projects supported under Water Technology Initiative (WTI) by DST

Project	Implementing Organization/Institute	Extract
To develop sustainable solar-powered wastewater treatment systems to improve/hygiene and sanitation in schools by adopting water recycling and online water quality monitoring Scope	Indian Institute of Technology Madras	Development of a sustainable treatment system that can effectively treat the wastewater generated from schools and also produces a reliable source of good quality water for hygiene and sanitation-related purposes. The technology includes a chain of treatment systems to ensure simultaneous carbon and nitrogen removal and determine optimal operating conditions for effective nitrification and denitrification in a single reactor system. Additionally, the present study stresses developing effective, low cost and reliable online monitoring sensors to check the quality of treated water, thus preventing the health risk associated with the reuse of treated wastewater. If the quality level is sufficient (low enough), an appropriate valve will be activated, and the water will be stored and re-used. The analysis result showed better removal efficiency of COD (80%), TSS (95%) and total nitrogen (40-50%). The principal output of the project involves a cost-effective and efficient treatment system to improve the overall sanitation at the grass-roots level and increase the awareness of water quality, conservation and reuse among the younger children and school teachers.
Structured Dialogues for Sustainable Urban Water Management and Integrative Design Framework for Fast Growing Livable Cities	State council of science technology & environment SCSTE, Meghalaya	Action research to employ technology intervention by constructing a wastewater treatment plant using locally available resources and bio-filter constructed at the vicinity of the fermentation tank to filter the foul-smelling water into clean, odourless water. The action research was carried out at Pongtung village. Results of water analysis from the treatment plant indicated an improvement in the water quality, which can be used for a lot of recreational activities like washing clothes, watering agricultural fields etc.
Implementation of various technologies addressing the state's local problems and challenges.	Punjab State Council for Science & Technology	Technology Development & Demonstrations • Setting up of Demonstration Units for preparation of Green Fuel from Paddy Straw for Industrial use • Designing of Machinery for Paddy Straw Briquetting in decentralized manner and studies for improvement of its life cycle • Artificial Intelligence for River Water Quality Monitoring • • Big Data Analytics for Environment Improvement
State Level Water Quality Analyses Laboratory in premises of UJS, Dehradun.	UCOST in collaboration with Uttarakhand Jal Sansthan (UJS) Dehradun & DAV PG College Dehradun. Funded by DST (GoI), New Delhi	
Soil nutrient profiling of the	Arunachal Pradesh State Council for Science & Technology (APSCS&T)	A study was also done to identify beneficial bacterial diversity from the undisturbed soil of Kimin and In Vitro screening of the beneficial microbial strains for their plant growth-promoting activities (PGP).

agricultural field of kimin area		
Waste water treatment technique	Jadavpur University, Kolkata	Development of Electrocoagulation and Electroflotation Enhanced Membrane Module (ECEFMM) techniques for waste water treatment. Electrocoagulation is a wastewater treatment technique that uses an electrical charge to change the particle surface charge, allowing suspended matter to form aggregates. Electroflotation separates suspended particles from water using hydrogen and oxygen bubbles generated by passing electricity through water. The innovation, an economically feasible wastewater treatment technology (both in terms of capital and recurring investment), has good market potential. The technology requires minimal manpower and does not need high-end technical adequacy for its operation, thus reducing the operational expense to a large extent. The recovered spent oil after oily wastewater treatment can be further used as an industrial burner oil, furnace oil, mould oil, hydraulic oil, etc. Thus, it creates an enormous revenue generation scope for low-income groups by selling this collected spent oil. The validation and testing of the prototype have been accomplished, and the pilot-scale validation and testing are on the verge of completion. This prototype innovation has proceeded towards level 6 of the Technology Readiness Level, and Dr Chiranjib Bhattacharjee has partnered with Concepts International for industrial collaboration and scale-up of the innovation. He plans to carry out a field run with the pilot-scale module, networking and field installation, and Commercialisation of the equipment through start-up.
Field level initiatives in consortia with R &D Ins and Community Demonstration of affordable Arsenic Removal Technology in rural areas of UP, WB and Bihar	IIT-Bombay, local community, NGO's	• 52 new Arsenic removal plants installed. • Generates 25 times less sludge than other processes • Cost -Re 1 per KL, relatively less compared to other processes • Capable of consistently delivering drinking water< 10 ppb. • Beneficiaries- 1870 families spread over 4 clusters in 46 sites.
Technology: Membrane Technology for drinking Water - Buja Buja Cluster, Mamsapuram and Thirupattur	Water Systems India Pvt Ltd	• Coagulation and Chlorination for domestic use. • Settlement and Flocculation for Waste Water treatment. • Waste Water treatment Plant –reuse it for irrigation and recharge the Groundwater table.
River Bank Filtration Technology in Uttarakhand	Convergent technology solutions through Consortia mode with R &D Ins and State Councils. Implemented by UCOST and UJS	• 30-60 KLPH safe water at each place. • Costs 1/10 of the conventional system. • Needs 20% area as opposed to typical treatment systems • 25% of the cost borne by Uttarakhand Jal Sansthan (UJS). • Beneficiary population-61,159. • Govts of Assam, Bihar, UP and WB requested services of UJS to replicate RBF technology.
Rain Water Harvesting,Chirawa	Dalmia Trust	• 685 Rainwater harvesting tanks prepared 137 lacs litre water storage capacity at the household level. • Almost 7500 family members are drinking safe water. • Four ponds were helping in the increase of groundwater by pouring more than 700 lacs litre water undertaken in village Kishorpura, Mahrampur, and Govindpura.in Chirawa block, Jhunjhunu District

Portable Water Purification System	CEERI Pilani	• A prototype has been developed as Dielectric Barrier Discharge (DBD) based plasma system for portable water purification at CEERI, Pilani, which will produce UV radiations in the germicidal wavelength and disinfect the impure water. • Approx cost-8 inch tube Mercury Free Plasma UV (MFP-UV) Lap Rs. 250 • Technology has been successfully transferred for commercialisation to Turners Pvt. Ltd. Jaipur.
Recycling of Waste Water-Improved Moving Bed Bio Film Reactor (MBBR)	SVECW, Bhimavaram	• Two 1.5 MLD Wastewater treatment plants demonstrating innovative MBBR Probiotics Technology has been established at SVECW, Bhimavaram • Conservation of freshwater through sewage water treatment.

DST-Intel Collaborative Research for Real-Time River Water and Air Quality Monitoring

Recognizing the importance of developing the online River Water and Air Quality Monitoring (WAQM) systems, DST, the Government of India, and Intel are collaborating to jointly initiate "DST-Intel Collaborative Research for Real-Time River Water and Air Quality Monitoring". This initiative aims to develop key technologies for sensing, communication, and analysis of large-scale data collected from autonomous networks of perpetual/long-lived sensor nodes, followed by integration and deployment for water and air quality monitoring in real-time. The Ganga, the largest and the most important river of India, with its watershed covering 10 Indian states, has been degraded due to charge of untreated sewage from urban centres, with the total wastewater generation from 222 towns in the Ganga basin reportedly 8250 MLD, out of which 2538 MLD is directly discharged into the river, 4491 MLD is disposed into its tributaries, and 1220 MLD is disposed on land or low lying areas. River Yamuna is another one of the grossly polluted rivers in the country.

To eliminate problems associated with manual monitoring, DST and Intel have come together to develop state-of-art solutions for real-time river water and air quality monitoring. This research aims to enable the development and eventual deployment of low-cost, low-power, autonomous wireless sensor networks to provide a fine-grained view of several critical waters and air quality metrics over large geographic areas (cities, rivers, watersheds etc.) as pre-remedial quality status. It would enable the assessment of the efficacy of post remedial interventions based on real-time reliable factual data. Such networks may also eventually replace the current paradigm of environmental quality management via localized stations. Developing such an Internet of Things (IoT)-based solution will require innovations in sensor technology for miniaturized platforms for continuous, always-connected multi-modal sensing, ultra-low power radios for efficient communication and energy harvesting technologies to enable very long or perpetual operation of sensor nodes. These key blocks will need to be woven together by a data analytics framework that spans edge devices, gateways, and cloud-based analytics to enable inference and sense-making in a low-latency manner.

APCTT promotes regional cooperation on science, technology, and innovation to achieve the Sustainable Development Goals (SDGs) by 2030. APCTT has been fostering inclusive partnerships between governments, research and development institutions, private sector and civil society for transfer, dissemination, and diffusion of environmentally sound technologies between countries in the Asia-Pacific Region. While developing partnerships and creating an enabling environment for innovation and technology transfer, the Centre not only contributes towards the SDGs 9 and 17 but also supports the other SDGs through specific technologies related to different SDG goals. The United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) is the regional development arm of the United Nations for the Asia-Pacific region. Some of the projects handled by them is shown in Table 13.

Table 13. Projects handled by ESCAP

Project	Extract
Protecting the Ocean	Marine and coastal ecosystems are the first line of defence from saltwater inundation and storms. However, rampant marine pollution, ocean acidification and warming, destructive fishing practices, unsustainable trade and transport, and inadequate coastal and marine governance threaten the health of our ocean and its capacity to nurture sustainable development. Countries in Asia-Pacific are major sources of ocean degradation and are highly vulnerable to its impacts. At the global level, Sustainable Development Goal 14 – Life below water – offers a framework on how countries can conserve and sustainably use the ocean, seas and marine resources for development. The United Nations Ocean Conference recently committed to halting and reversing the decline in the health and productivity of the ocean and its ecosystems, ensuring to protect and restore its resilience and ecological integrity. It also recognized that the well-being of present and future generations are inextricably linked to the health and productivity of the oceans; and stressed the importance of enhancing understanding of the health and role of the oceans, including through assessments on the state of the ocean, based on science and traditional knowledge systems.
Safeguarding ecosystems' health	EDD supports a transition to agroecology in Asia and the Pacific as an example of low carbon, risk-informed, resilient, regenerative, and sustainable agricultural practices that apply ecological principles to food systems. A regional push to support the transition towards agroecology in Asia and the Pacific would support environmental progress in the region, in line with the principles of planetary health.

Gaps identified

1. Need for choosing the water quality parameters carefully. The water quality indices (WQI) should not only be deemed fit for the study of a particular area or watershed but should be suitably applicable on a global scale. Also, each index developed for a particular end-use of water such as drinking, irrigation, industries, heavy metals, etc., which considers specific parameters needs a comprehensive assessment.

2. All the tools adopted for conducting surveys or recording responses from people of the regions and, in most cases, from various experts is based on preparing author questionnaires, conducting surveys, etc. which may prove inconsequential to water bodies other than those considered for the study. Additionally, these proposed water quality indexes (WQI) may often be misleading, creating ambiguities among other researchers worldwide.

3. The efficacy assessment of the proposed or developed WQIs is often neglected. There is significant scope in employing various tools (neural networks, regression models), mainly introducing the concept of sensitivity analysis to the domain of water quality indexing, which would help address the reliability of the indices.

4. Newly emerging techniques in the field of water quality indexing such as multivariate statistics, probability, randomness of water quality datasets (information entropy) need further research for development of a new, more comprehensive water quality index.

5. In India, in both industry and academics majority of the sensor R&D happens at the system integration level rather than sensor material development. More industry-academic collaboration should happen to develop materials, architecture, fabrication, packaging, and data analysis.

Highlights from interviews with people of interest and stakeholders

Prof. Renganathan and his team from IIT, Madras has developed a low cost, field-deployable colourimetric paper-based microfluidics sensor (LP-µPADs) and adsorptive colourimetry sensor to meet the Affordable, Sensitive, Specific, User-friendly, Rapid and robust, Equipment-free and Deliverable to end-users (ASSURED) criteria set by WHO for the detection of antimicrobials in water bodies as a viable tool for environmental surveillance. Periodic monitoring of antimicrobials and antibiotic-resistant genes is the key to assessing India's current Antimicrobial Resistance (AMR) situation. The alpha version of the prototype is ready and tested for its performance and statistical validity in the field. The aim is to enable community-driven microfluidics and facilitate mass surveillance. The production cost of a paper-based sensor is ~ ₹ 5 per assay, and adsorptive colourimetry is ~ ₹ 15 per assay. The complete details of the interview are given in Annex I.

Prof. Ramamurthy and his team from IISc, Bangalore, have designed and developed novel molecular architectures and fabricated a solid-state sensing device for explicitly detecting a variety of analytes like VOC, nitrates, heavy metals like lead, mercury, and chromium ions, as well as iron, fluoride, arsenic ions, and biological organisms such as E. Coli. The most important aspect of the research is decoding and elucidating the interaction between sensing molecules and analytes. Complete interview details are given in Annex I.

Section 3: LEMS Monitoring for Air Pollution

Hidden air pollutants on the rise in India and UK

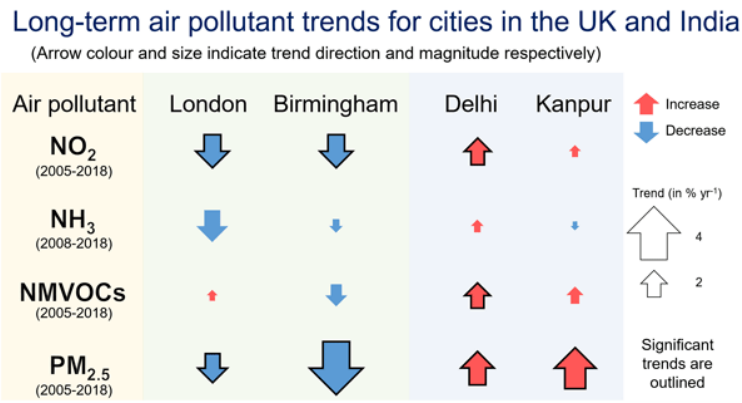
Recent comparative studies have shown that increases in $PM_{2.5}$, fine particles and nitrogen dioxide (NO_2) are the leading contributors to premature death from exposure to air pollution in Kanpur and Delhi. The increases in $PM_{2.5}$ in Kanpur, identified by the World Health Organization (WHO) as the most polluted city in the world in 2018, were both significant and substantial, at 3.1% per year (News, 2021). The researchers speculate that these increases are due to increasing vehicle ownership and industrialisation.

Observed is increases in the air pollutant formaldehyde formed from chemicals collectively known as non-methane volatile organic compounds or NMVOCs; formaldehyde is an ideal marker for NMVOCs emissions. NMVOCs are emitted from many sources in cities, including vehicles, solvents, building materials, adhesives, and household and personal care products - and interact with other chemicals to form $PM_{2.5}$ and ozone (Karn Vohra, 2021).

In London, levels of $PM_{2.5}$ and NO_2 were found to be decreasing and the researchers noted that this reflects the success of policies targeting these emissions sources. This is in stark contrast to Kanpur and Delhi, where increases in these pollutants indicate that air pollution policies and mitigation measures - including the roll out of controls in the industrial and transport sectors - are having a limited effect.

The researchers highlight the importance of satellite data from space-based instruments in helping derive long-term pollution trends to monitor emissions and inform policies to reduce pollution, with their results confirming that vigilance and urgent action are needed across the globe to reduce air pollution levels (Karn Vohra, 2021). Some of the latest data are shown in (NUMBEO) Table 14, Figure 5, Figure 6.

Table 14. Long-term pollutant trends for cities in the UK and India



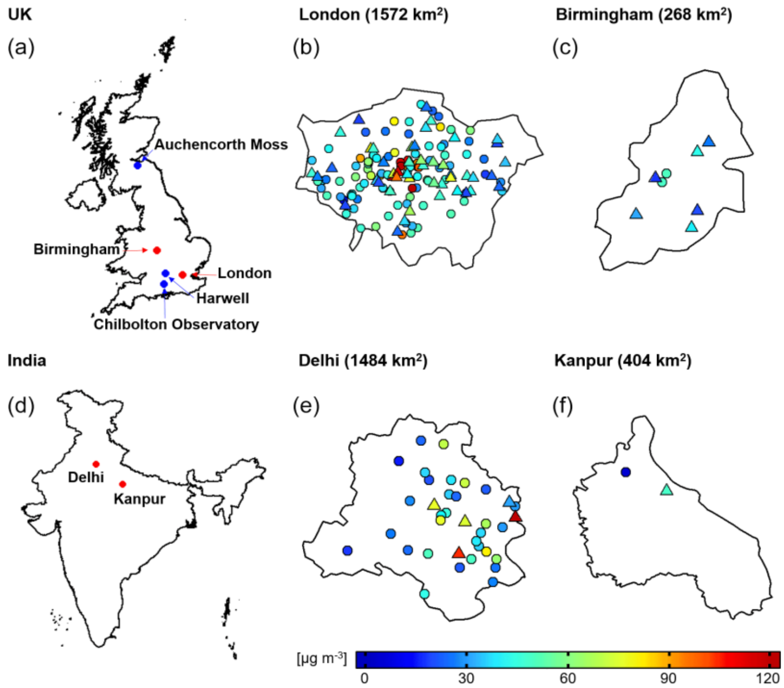


Figure 5. Spatial extent of surface NO2 monitoring stations in London (b), Birmingham (c), Delhi (e), and Kanpur (f). Panels (a) and (d) show the location of the target cities (red) and UK sites that are part of the European Monitoring and Evaluation Programme (EMEP) (blue). Panels (b), (c), (e), and (f) show the locations of local authority regulatory NO2 monitoring stations within the administrative boundaries of each city, coloured by mean midday NO2 for 2005–2018 and separated into sites used (triangles) and not used (circles) to assess satellite observations of NO2 (see text for details). The surface area of each city is indicated. Country and city boundaries are from GADM version 3.6 (GADM, 2018) and DataMeet (DataMeet, 2018).

Air pollution data from World Health Organization

	London	Delhi
PM_{10}	23	292
$PM_{2.5}$	12	143
PM_{10}Pollution Level:	Low to Moderate	Extremely High

Pollution London vs Delhi

	London Improve Data	Delhi Improve Data
Air Pollution	High 63.51	Ver
Drinking Water Pollution and Inaccessibility	Low 31.77	
Dissatisfaction with Garbage Disposal	Moderate 41.45	
Dirty and Untidy	Moderate 48.52	
Noise and Light Pollution	Moderate 55.09	
Water Pollution	Moderate 40.82	
Dissatisfaction to Spend Time in the City	Moderate 45.11	
Dissatisfaction with Green and Parks in the City	Very Low 19.69	Mo
Contributors:	*369*	*680*
Last Update:	*March 2022*	*March 2022*

Figure 6. Air pollution data from WHO

UK

Air pollution is recognised as one of the greatest environmental threats, both in the UK and globally. It is also an important public health issue, associated with 7 million deaths globally each year in addition to the damage it does to crops and the ecosystem. Yet although we know that the gases and particulate matter produced by burning fuel are harmful, there is still a great deal we don't know about how individual pollutants contribute and combine to affect human health over the short and longer term.

High levels of pollutants including gases (such as nitrogen dioxide) and particulate matter carry harmful consequences for both human health and the environment. More research and evidence are needed to better understand air pollution and inform the changes in policy and people's behaviour that can limit its negative impacts (Potts, 2021; Smith, 2013).

Air pollution research requires a huge diversity of expertise which ranges from understanding environmental processes, to monitoring, assessing and addressing impacts of air pollution and associated mitigating policies (Affairs, 2014). Furthermore, it is an issue that is intrinsically linked to other environmental, public health and urbanization challenges. Reducing air pollution will have co-benefits in terms of greenhouse gas emissions and will improve public health and well-being (HSE).

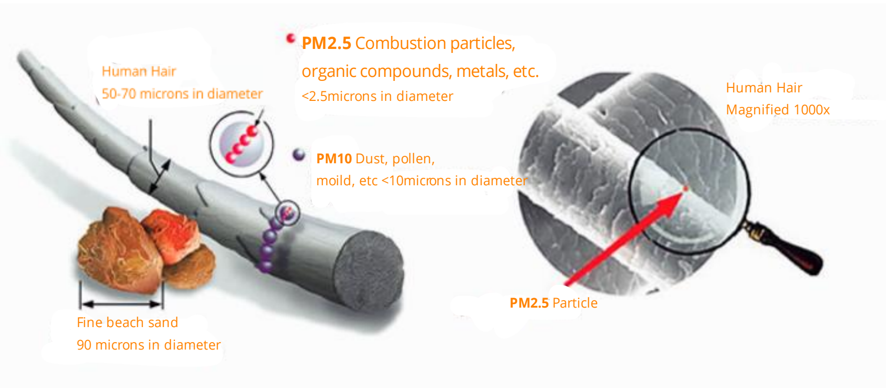
The main research into air pollution strives to improve understanding with respect to the evolution of human activity and resultant emissions, complex atmospheric chemistry and transport processes, the specific health consequences of exposure to different air pollutants on individuals, new measurement and sensing capabilities and appropriate technologies and policies to mitigate the impacts of air pollution globally (Walters, 2010, Mills and Peckham, 2019). Atmospheric composition data from satellite platforms offers great potential for improving the understanding of anthropogenic emissions.

There are five key areas: air pollution science, new tools for monitoring and modelling air quality, control and prevention, co-benefits, and policy (Cole et al., 2005). Collaboration and contribution from industrial and government stakeholders, policymakers and members of the public are important steps towards better and informative decisions resulting in broader co-benefits. "We tend to think about air pollution as a technological problem requiring better fuel efficiency or emissions control, but the types of policy that you put in place can have broader co-benefits," says Dr de Nazelle, Imperial College. "For example, if we encourage decision-makers to create cities that are more walking- and bicycle-friendly, and friendlier to public transport users, then not only are we improving air pollution but we're also getting people to be physically active or creating environments where people can talk to each other. To me, the air quality network is a way to think a bit beyond air pollution."

"By understanding the actual needs on the ground – both from an industrial and a policy perspective – and having a better understanding of how the system works, we believe that we can have a greater impact by ensuring that our research is useful and is used," says Dr de Nazelle.

Air quality refers to the condition of the air around us and whether it contains pollutants (chemicals or substances that are not normally there). This is where we get the term 'air pollution' from. Most of the air pollution in London is man-made, being produced by traffic, industry, heating and burning solid fuels. The main pollutants are:

- Nitrogen dioxide (NO_2), a gas which is often produced after fuel is burnt and mixes with oxygen in the air. When you breathe in air with a lot of NO_2, it can irritate your airways which in the short term can cause coughing, wheezing or difficulty breathing. Longer exposures may contribute to the development of asthma and respiratory infections.
- Particulate matter (PM) are specks of solid material or liquid that are suspended in the air (some of which is coming from residue/particles from tyres). Some of the larger particles may be visible, but many are much smaller so can only be seen with a microscope. All PM can be damaging to human health when breathed in, but especially the very fine particles which are small enough to go deeper into your lungs and also into your blood which carries them around your body.



Air pollution is often referred to as an invisible killer, because unlike cigarette smoke, it is less obvious when you are breathing it in. Globally, more than 80% of people living in urban areas are exposed to pollution levels that exceed World Health Organisation limits (WHO, 2021). It's not only big cities like London that are affected – even small, and relatively leafy, but green places like Oxford have also been found to have dangerously high levels of pollutants like nitrogen dioxide. The new WHO Global Air Quality Guidelines (AQGs) from 2021 demonstrate the harmful effects of air pollution on human health at considerably lower concentrations than previously thought. The guidelines propose new air quality standards to safeguard people's health by lowering levels of important air contaminants, some of which are also linked to climate chan

Table 15. Recommended 2021 AQG levels compared to 2005 air quality guidelines

Pollutant	Averaging Time	2005 AQGs	2021 AQGs
$PM_{2.5}$, µg/m^3	Annual	10	5
	24-hour[a]	25	15
PM_{10}, µg/m^3	Annual	20	15
	24-hour[a]	50	45
O_3, µg/m^3	Peak season[b]	-	60
	8-hour[a]	100	100
NO_2, µg/m^3	Annual	40	10
	24-hour[a]	-	25
SO_2, µg/m^3	24-hour[a]	20	40
CO, mg/m^3	24-hour[a]	-	4

Although it is less visible than cigarette smoke, the pollutants emitted from burning fuels like wood, coal or petrol are similar. Across the European Union, air pollution is estimated to contribute to around 467,000 premature deaths each year – 40,000 of them in the UK. Lung cancer, chronic obstructive pulmonary disease and asthma have all been associated with higher levels of airborne particulate matter in the environment. But the lungs aren't the only body part affected: spikes in the concentrations of fine particulate matter and nitrogen oxides are also associated with increased hospital admissions for heart attacks, heart failure, heart rhythm disturbances and stroke (Desikan, 2016; Crichton, 2016; Butland, 2017; Andersen, 2012).

There's even evidence that tiny airborne particles can enter the brain: some studies suggest that people living close to very busy roads are at increased risk of dementia, while others suggest that school children can have their cognitive development impaired (Milojevic, 2021; Hedges, 2019; Gale, 2020). The precise mechanisms by which air pollution contributes to these very different diseases are still unclear, but they are all thought to have one thing in common the smaller the particle deeper it penetrates into the respiratory system and triggers inflammation.

Better understanding of how airborne pollutants interact to affect individuals' health. Most studies have focused on the health impact of air pollutants at a population level, rather than tracking individuals' exposure patterns and correlating these with health outcomes. These have shown us, for example, that children attending schools near busy roads experience more asthma attacks, but they don't tell us much about the risks to an individual child (Khreis, 2018; Kelly, 2021). This is now beginning to change, thanks to the development of cheaper wearable sensors that can monitor exactly what someone is being exposed to as they go about their daily lives (Dong, 2019; Dam, 2017; Al Mamun, 2019).

However, to effectively tackle air pollution, researchers first need to know precisely what they are dealing with and where it's coming from. Particulate matter can refer to anything that floats in the air, including particles generated by human activities such as burning fuel, but also those from more natural sources such as pollen and sea spray. When we are exposed to various substances in our environment, including air pollutants, these trigger characteristic molecular signatures which can be detected in our blood and body tissues. This could help for better understanding of their effects on the body and how they might contribute to long-term disease risk. They are also studying people's genes to better understand how their patterns of expression change in response to poor air quality. Not only could this provide new insights into why some people are more susceptible to the effects of air pollution than others, it may also help determine whether air pollution is the source of any symptoms reported by individual patients.

To date, much of the focus in terms of trying to reduce air pollution has been on measuring and reducing the emissions from vehicles. A recent report (EPHA, 2021) shows that electrical cars mainly use "regenerative braking" (oppose to internal combustion engines using disc brakes) as it restores braking energy back to the car's battery to power the car. This process reduces the need to use brakes and reduces the particle emission. In addition, electrical cars are fitted with "special tyres" designated to cope with the heavier weight of batteries so more studies are required to measure and compare the particle pollution from tyres and compare with other heavy vehicles. According to the Organisation for Economic Co-operation and Development (OECD) electrical vehicles contribute less PM2.5 and PM10 than diesel and petrol cars. Since the 1970s, European Union regulations have meant that new cars have to meet certain fuel-pipe emissions standards to try and cut air pollution. Similar standards exist in many other countries as well. Yet, as the recent "Dieselgate" scandal surrounding the car manufacturer Volkswagen showed, such standards are vulnerable to manipulation: Volkswagen's engineers intentionally programmed some of their diesel engines to activate emissions controls only during laboratory testing, but when the cars were driven in the real world their nitrogen dioxide emissions were many times higher.

Attempting to overcome this problem, Dr Stettler and his colleagues from Imperial College have been testing a real-time vehicle emissions monitoring system in diesel, gasoline and hybrid cars to try and gain a clearer picture of their real-world emissions. A detailed analysis (Koudis, 2018; Koudis, 2017) was published of the carbon dioxide and nitrogen dioxide emitted by 149 different passenger car models – accounting for 56% of all passenger cars sold in Europe during 2016. "In general, we found that diesel cars are worse for nitrogen oxides but better than petrol cars in terms of carbon dioxide emissions," Dr Stettler says. "It potentially leads to a trade-off that we have to face about what's more important to us: ***is it air quality, or is it climate change?"***

Someday, such technology could even be used to implement varying road charges based on the actual emissions a vehicle is spewing out, rather than the current flat rate car tax system that operates in the UK and elsewhere.

Researchers are now trying to use real-time emissions monitoring to generate a more detailed picture of where these real-world emissions are occurring. Tailpipe emissions are higher when vehicles accelerate, and high concentrations of air pollutants tend to be found near traffic lights, where such acceleration events occur frequently – but real-time monitoring might reveal other air pollution hotspots in our towns and cities as well. For instance, although people often focus on the pollutants coming out of car tailpipes, another source is brake pads: the friction generated when they press against the wheels release tiny metallic particles, which have been less well studied, but are potentially more toxic. In the short term, such knowledge could be used to help reduce people's exposure to vehicle emissions. It would be possible to try and reduce the amount of air pollution pedestrians are exposed to through smarter phasing of traffic light crossing timings with vehicle movements.

Longer-term, drivers could potentially be provided with real-time feedback on their vehicles' emissions to encourage them to drive in a less polluting way. For instance, some studies have suggested that aggressive driving that involves a lot of sharp acceleration and braking can as much as double the amount of nitrogen oxides emitted by vehicles; it also increases fuel consumption, potentially costing the driver money.

An industry/academic partnership (The Intel Collaborative Research Institute (ICRI)) involving Intel Laboratories, Imperial College London and University College London – has been working across several London boroughs to develop and deploy a network of air quality sensors attached to trees and lamp-posts, as well as systems that process the data they generate to enable real-time analysis of air pollution levels on a street-by-street basis. Another group from Cambridge developed open-hardware device to monitor air quality and road surface quality (open-seneca project) and designed a portable, low-cost, air quality monitor.

The traditional air quality measurement system used across London consists of around 150 sensors that each cost between £10,000 and £100,000 and require regular maintenance. In case a larger number of more geographically granular air quality sensors are deployed then this could potentially accrue more information about micro-changes in air quality.

The sensors that ICRI has developed are smaller and less accurate than the gold-standard ones that are in widespread use, but they are cheaper and easier to deploy, and don't need regular maintenance to continue to operate. ICRI researchers have also developed software that will help enable useful data to be recovered from the sensor networks.

The hope is that such sensors could provide local authorities with more detailed data about pollution hotspots, enabling them to produce more accurate air quality reports, and even rapidly identify areas of slow-moving traffic. This real-time information could also be fed back to drivers, providing further encouragement to e.g. turn off idling engines or adopt other behaviours to improve air quality.

Trying to change the behaviour of individual motorists is one thing, but to significantly improve the quality of the air we breathe, action is also needed at a national and international level.

Article 5 Assessment (Bush, 2000) discusses the methodology, requirements and monitoring linked with NO_2, PM10, SO_2, Pb in the UK.

Acting against air pollution costs money, which governments and large businesses are often reluctant to part with – unless they can see a quantifiable benefit.

Until recently, no-one had put a price on local health savings that might be made by addressing air pollution. Imperial researchers in collaboration with the UK Health Forum, were recently commissioned by Public Health England to calculate the health and social care costs of exposure to fine particulate matter and nitrogen dioxide. The figure they came up with for 2017 was £157 million – based on data for diseases with a well-established connection to air pollution.

Assuming levels of these pollutants remain the same, the researchers estimate that the total cost of air pollution to the NHS and social care between 2017 and 2035 could be as high as £18.6 billion – arising from 2.5 million new cases of coronary heart disease, stroke, lung cancer, and many other diseases.

Neither does this analysis consider the broader co-benefits of tackling air pollution, such as reducing the damage to buildings or ecosystems, encouraging more people to cycle to work and therefore get more exercise, or helping to meet climate change targets.

Even so, when funding is limited, it is important to make sure that it is spent in the most effective way: encouraging more people to walk or cycle to work instead of driving may sound like a great way of improving people's fitness as well as reducing air pollution – but only if exercising in polluted areas doesn't undermine their health in other ways. It is therefore essential that such policies are grounded in evidence.

Quantifying the co-benefits of air pollution could also help decision-makers make better choices when several different policies are on the table.

There are many sources of air pollution in London which produce different pollutants. Most pollution is man-made and comes from: heating of buildings (especially houses); road traffic; and non-road machinery (such as that used in construction). In congested areas such as around the A40 Westway, and the Cromwell and Earl's Court Roads, a lot of the air pollution (both NO_2 and PM) comes from large volumes of traffic and exhaust emissions from older and diesel vehicles.

Londoners also get air pollution blown in by the wind from outside London and even beyond the UK, often from farming and industry. All of the pollution mentioned so far occurs outside, but there is also indoor pollution which mostly comes from cooking and heating, cleaning chemicals and personal hygiene products, as well as new carpets, new furniture and paint. Ventilating a room when you create these pollutants is very important and can be as simple as opening a window or switching a kitchen or bathroom fan on.

Being exposed to air pollution every day can have a deleterious effect on health, particularly for children because their lungs are still developing. The effects of bad air pollution have been shown to include harm to the brain, heart and immune system (which fights against infection). The pollution is also dangerous for older people and those with existing health issues such as asthma, other lung problems (for example bronchitis) and heart conditions.

There are many projects in London that help to reduce air pollution, such as school street closures, introducing cleaner buses, and the Ultra Low Emission Zone (ULEZ), which extended out to the north and south circular roads in October 2021.

There is also a lot that we can do as individuals, including making fewer journeys in vehicles and increasing our walking, cycling and scooting (collectively known as 'active travel'). As well as not contributing to local air pollution, the physical exercise associated with active travel can be beneficial to our health while choosing low pollution routes can reduce our exposure to poor quality air.

There are several recent and ongoing developments related to the usage of wearable sensors for environmental monitoring (Zhou, 2022; Motlagh, 2021; Marquart, 2021; Hernandez-Gordillo, 2021; Helbig, 2021; Becker, 2021).

Some examples of LEMS that are currently being manufactured in the UK are depicted in Table 16, Table 17, Table 18

Table 16. Examples of LEMS for monitoring air pollution manufactured in the UK

Air sensors											
Company(Based in)	**Air sensors**	**Picture**	**Cost**	**Portable**	**Dimentions(mm)**	**weight**	**Used by non-professional?**	**Expected lifespan**	**/outdoor measure**	**Parameters**	**Technical specifications link**
AQMesh (UK)	AQMesh		3600£	No	170 x 220 x 250	2-2.7kg	Yes	n/a	Outdoor	PM, CO, Noise, Ultrasonic wind speed, Temperature, Pressure, Relative Humidity	https://www.aqmesh.com/products/technical-specification/
Awair (UK)	Awair Omni		640£	Yes	n/a	n/a	Yes	5 to 7 years	Indoor	Temperature, relative humidity, Carbon dioxide, TVOC, PM2.5, Light, Noise, Awair score,	https://drive.google.com/file/d/1RuUmo0cao_LbFmeFXq8s9TilHv8GKcMr/view
Flamefast (UK)	FGSD		420£	No	152 x 110 x 200	n/a	Yes	2 to 10 years	Outdoor	Ammonia	file:///C:/Users/marta.jesus/AppData/Local/Packages/microsoft.windowscommunicationsapps_8wekyb3d8bbwe/LocalState/Files/S0/3/Attachments/Information%20-%20FGS[1788].pdf
Temtop	Temtop CO2 M2000		220£	Yes	73.5 x 223.5 x 37.5	0.800kg	Yes	2 years	Indoor	PM2.5/PM10, Formaldehyde, CO2, Histogram, Temperatue and Humidity	https://www.amazon.co.uk/dp/B07DTR31RK/ref=syn_sd_onsite_desktop_173?pd_rd_plhdr=t&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzUDgvWDhCRUQxNERElmVuY3J5cHRlZElkPUEwNDQ4NDk0MkVBNlIOTVdKRzZlTyZlbmNyeXB0ZWRBZElkPUEwNzUzNlU0MktKWFlYNlITRllVU [illegible]
Alphasense (UK)	OPC-N3		352£	No	75 x 63.5 x 53	0.105kg	Yes	3 to 5 years	Outdoor	Particulate matter	https://www.alphasense.com/wp-content/uploads/2019/03/OPC-N3.pdf
Alphasense (UK)	VOC-A4		97.70£	No	20.2 x 20.8	0.600kg	No	3 to 5 years	Outdoor	VOCs	https://www.alphasense.com/wp-content/uploads/2021/08/VOC-A4-Aug-21.pdf

Table 17. Air pollution sensor characteristics

Sensor	Measures	Type	Units	Range	LOD
Q46D	Dissolved oxygen	Fluorescence	ppm	0 to 40.00 ppm	
Q46N	Total ammonia, Free ammonia and monochloramine	Amperometric membraned cell	ppm	Ammonia: 0 to 20.00ppm Monochloramine: 0 to 10.00 ppm	
Watr	Conductivity		ms/cm	0 to 100 ms/cm	0.01 ms/cm
	Dissolved oxygen		mg/L	0 to 20 mg/L	
	turbidity		Chlorophyll: µg/L Nephelometer: FTU	Chlorophyll: 0 to 100 µg/L Nephelometer: 0 to 100 FTU	0.1% of full range
	pH		pH	0 to 14 pH	0,01
	Other parameters include: Salinity, BOD, COD, TDS, Ammonia, sulfide, sulfite, nitrates, ORP, metals, rhodamine, crude oil, blue/green algea, phenol				
SC200	17 parameters				
Orion star A329	pH		pH	0 to 14 pH	0,01
	mV/RmV		mV	+- 2000.0 mV	0.1 mV
	ISE		ppm; M; mg/L; %; ppb; none	0.0001 to 19900	0.001
	Conductivity		µS	0.001µS to 3000µS	0.001µS
	Resistivity		ohm	2 to 100 ohm	1 ohm
	Salinity		psu; ppt	0.06 to 80.00 PSU or 0.05 to 42.00 ppt	0.01 PSU or 0.01 ppt
	TDS		ppt	0.001 to 200.0 ppt	0.001 ppt
	Dissolved oxygen		mg/L	0 to 90 mg/L	0.1 mg/L
Aquaread AP-2000	Dissolved oxygen	Optical DO sensor	mg/L	0 to 50.00 mg/L	0.01 mg/L
	Conductivity		mS/cm	0 to 200 mS/cm	
	TDS		mg/L (ppm)	0 to 100 000 mg/L	
	Resistivity		Ω.cm	5Ω.cm to 1MΩ.cm	
	Salinity		PSU	0 to 70 PSU or 0 to 70 ppt	0.01 PSU or 0.01 ppt
	Seawater specific gravity		σt	0 to 50 σt	0.1 σt
	pH		pH	0 to 14 pH	0.01 pH
	ORP		mV	±2000mV	0.1 mV
	Ammonium	Ion selective sensor	mg/L (ppm)	0 to 9000 mg/L	
	Ammonia	Ion selective sensor	mg/L (ppm)	0 to 9000 mg/L	
	Chloride	Ion selective sensor	mg/L (ppm)	0 to 20000 mg/L	
	Fluoride	Ion selective sensor	mg/L (ppm)	0 to 1000 mg/L	
	Nitrate	Ion selective sensor	mg/L (ppm)	0 to 30000 mg/L	
	Calcium	Ion selective sensor	mg/L (ppm)	0 to 2000 mg/L	
	Turbidity	Optical Electrode	NTU	0 to 3000 NTU	
	Chlorophyl	Optical Electrode	µg/L (ppb)	0 to 500.0 µg/L	
	Phycocyanin (fresh BGA)	Optical Electrode	cells/mL	0 to 300000 cells/mL	1 cell/mL
	Phycerythrin (marine BGA)	Optical Electrode	cells/mL	0 to 200000 cells/mL	1 cell/mL
	Rhodamine	Optical Electrode	µg/L (ppb)	0 to 500 µg/L (ppb)	
	Fluorecein	Optical Electrode	µg/L (ppb)	0 to 500 µg/L (ppb)	
	Refined oil	Optical Electrode	µg/L (ppb)	0 to 10000 µg/L (ppb) (Napthalene)	0.1 µg/L
	CDOM/FDOM	Optical Electrode	µg/L (ppb)	0 to 20000µg/L (ppb) (Quinine sulphate)	

Table 18. Sensors and Hidden Cost

Company	Sensor name	Hidden Cost
AQMesh	AQMesh	PM pod costs 3600£; CO pod costs 3600£; Noise pod costs 200£; Ultrasonic wind speed costs 3500£. Data storage (optional) Annual contracts for SIM is 150£/Pod or on demand data is 150£/Pod and can be accessed via Web app or API. Electrochemical CO sensor- 182£ (lifespan 24 months) Optical Particle Counter- 525£
Awair	Awair Omni	After the first 3 years – 12 months of Dashboard and API access for 180£/Omni/year
Flamefast	FGSD	Annual calibration: needs a cylinder of calibration gas and possibility to employ someone for calibration = 195£ + VAT
Temtop	CO2 M2000	No hidden costs
Alphasense	OPC-N3	Interface w/ software = 61£ + Connector cable = 5£ Delivery= 20£
Alphasense	VOC-A4	Individual Sensor Board = 63£ + Fittings for ISB= 4.60£ Delivery= 20£

Some unhealthy exposures are reported in (Omidvarborna et al., 2021) and data summarized in the Table 19.

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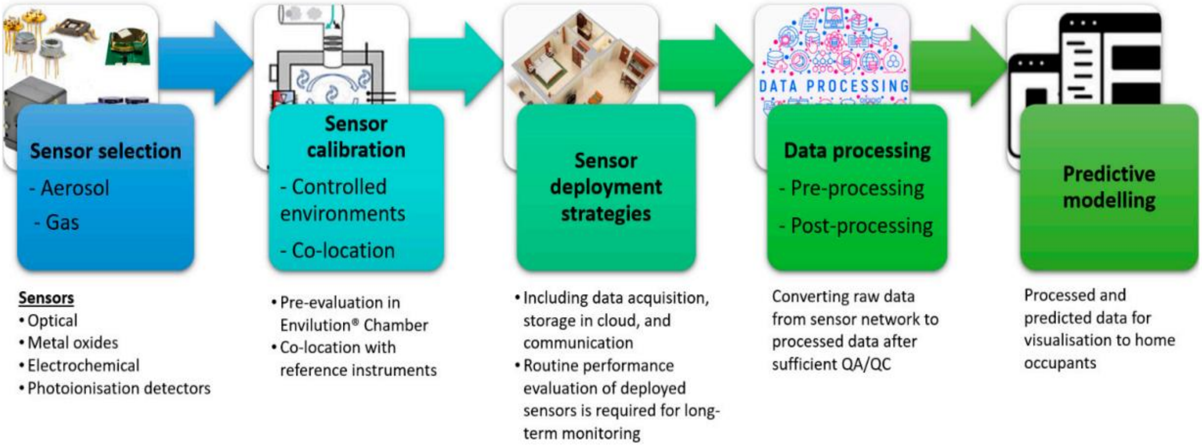
Table 19. Pollutants

Pollutants	Indoor Air	Outdoor Air
Benzene (C_6H_6) [μg m^{-3}]	Carcinogenic compounds, no safe level of exposure recommended risk of leukaemia estimated as 6×10^{-6} at 1 μg m^{-3}, World Health Organisation (WHO).	5 (annual) European Union (EU) 1.7 (annual) WHO
CO [mg m^{-3}]	100 (15 min–once per day) 35 (1 h–once per day) 10,000 (8 h) 7 (24 h) all from WHO.	10 (max daily 8 h mean) EU 30 (1 h) WHO 10 (8 h) WHO
CO_2 [ppm]	<1000 (hygienically harmless) 1000–2000 (elevated) >2000 (hygienically unacceptable) all from AIR.	405 (by climate.gov, accessed on 21 March 2021)
HCHO [μg m^{-3}]	100 (30 min) WHO	N/A
Naphthalene [μg m^{-3}]	10 (annual) WHO	N/A
NO_2 [μg m^{-3}]	200 (1 h) WHO 40 (annual) WHO	200 (1 h) EU/WHO 40 (annual) EU/WHO
O_3 [μg m^{-3}]	N/A	120 (max daily 8 h mean) EU 100 (8 h) WHO
PAH (benzo[a]pyrene) [μg m^{-3}]	All indoor exposures relevant to health, lung cancer with risk of 8.7×10^{-8} at 1 μg m^{-3}.	1 (annual) EU 0.12 (annual) WHO
$PM_{2.5}$ [μg m^{-3}]	10 (annual) WHO 25 (24 h) WHO	10 (annual) WHO 25 (24 h) WHO 25 (annual) EU
PM_{10} [μg m^{-3}]	20 (annual) WHO 50 (24 h) WHO	20 (annual) WHO 50 (24 h) WHO 40 (annual) EU 50 (24 h) EU
Tetrachloroethylene [μg m^{-3}]	250 (annual)	N/A
Trichloroethylene [μg m^{-3}]	Carcinogenicity with risk of 4.3×10^{-7} at 1 μg m^{-3}	N/A
TVOCs [a] [mg m^{-3}]	<0.3 (no hygienic objections) >0.3–1 (no relevant objections) >1–3 (some objections) >3–10 (major objections) >10–25 (not acceptable)	N/A

Note: N/A refers to not available; AIR refers to German Committee on Indoor Guide Values, formerly known as “Ad-hoc AG”. a Total VOCs, defined by the International Organisation for Standardisation (ISO) 16000-6.

Some essential steps toward a successful implementation of smart indoor sensor network in achieving appreciable indoor air quality (IAQ) and health benefits to home occupants are:



Some advantages and disadvantages of different technologies used for LCSs are summarized in Table 20:

Table 20. Sensor technologies

Sensor Technology	Known for	Summary of Pros and Cons
Electrochemical	NO_2, SO_2, O_3, NO, CO, NH_3 and VOCs [1]	√ Good sensitivity, from mg m^{-3} (potentiometric) to µg m^{-3} (amperometric). √ Fast response time (30–200 s). [2] √ Small in size (20 mm) and low power consumption (µW). √ Long-term stability with acceptable drift values (between 2% and 15% per year) reported for the commercial ECs. × Large in size, complicated, vulnerable to poisoning, and shorter life span (~1–3 years). × Highly sensitive to change in meteorology (temperature and RH variations) depending on electrolyte. [3] × Show cross-reactivity with similar molecule types. × More expensive than MOx gas sensors.
MOx	CO, CO_2, H_2, O_3, NH_3, NO, NO_2, NOx, CH_4, C_3H_8 and VOCs [4]	√ Good sensitivity, from mg m^{-3} to µg m^{-3} (ppb level) and relatively long lifetime (>5 years). √ Small in size (few millimetres) and long-lasting/light weight (few grams). √ Least power intensive (<1 W) – but higher than PIDs. × Results are affected by temperature and RH variations. × Long response time (>30 s; some cases 5–50 min), long stabilisation period before measurements (~24 h), and longer-term performance drift. × Poor recovery to achieve initial status under a change in experimental condition or exposure to a high concentration of target gases. × Output depends on the history of past inputs. × Instability over time. [5]
PID	VOCs [1]	√ Small in size with moderate price (approximately 400€ for a sensor to ~5000€ for a handheld device). √ Good sensitivity, down to mg m^{-3}, some down to µg m^{-3}. √ Limited temperature dependence and RH effects. √ Very fast (a few) response time. × Not selective: reacts to all VOCs that can be ionised by the UV lamp. Proper calibration and maintenance may be needed. × Significant signal drift.
Optical particle counter	PMs	√ Fast response time (in a second). √ Sensitivity in the range of 1 µg m^{-3}. √ Able to identify the size of the particle in the size of PM_{10} and $PM_{2.5}$. × Conversion from PM counts to PM mass with the theoretical model. × The measured signal depends on a variety of parameters such as particle shape, colour and density, RH, refractive index, etc. × Unable to detect ultrafine particles. [6]

Optical	CO and CO_2	√ Good sensitivity for CO_2 (350–2000 ppm). √ Selectivity is good through characteristic CO_2 IR spectra. √ Response time 20–120 s. √ Limited drift over time of the sensor calibration. × Need for correction for the effects of temperature, RH and pressure.

Other research groups report the "ultimate" sensing material for air quality monitoring discussing electrical and optical methods of detection (Buckley et al., 2020). A recent case study in Sheffield demonstrates using environwatch E-motes employed for air quality where collection of high-resolution spatial and temporal data in real time is done (Munir et al., 2019). Researchers discuss the potential of Low-cost PM sensors for improvement of monitoring resolution in a cost-effective manner but there are doubts regarding data reliability. In any case the study shows that low-cost PM sensors can be quite valuable and suitable to detect localized airborne PM concentrations (Bulot, 2019; Ottosen, 2019).

The conducted study highlights paired approach with machine-learning calibration technique to reduce the cost of air pollution measurements (Nowack et al., 2021).

In summary full range of socio-technical issues is essential to realize the full potential of sensor network technologies for society and the environment Figure 7 (Mao et al., 2020).

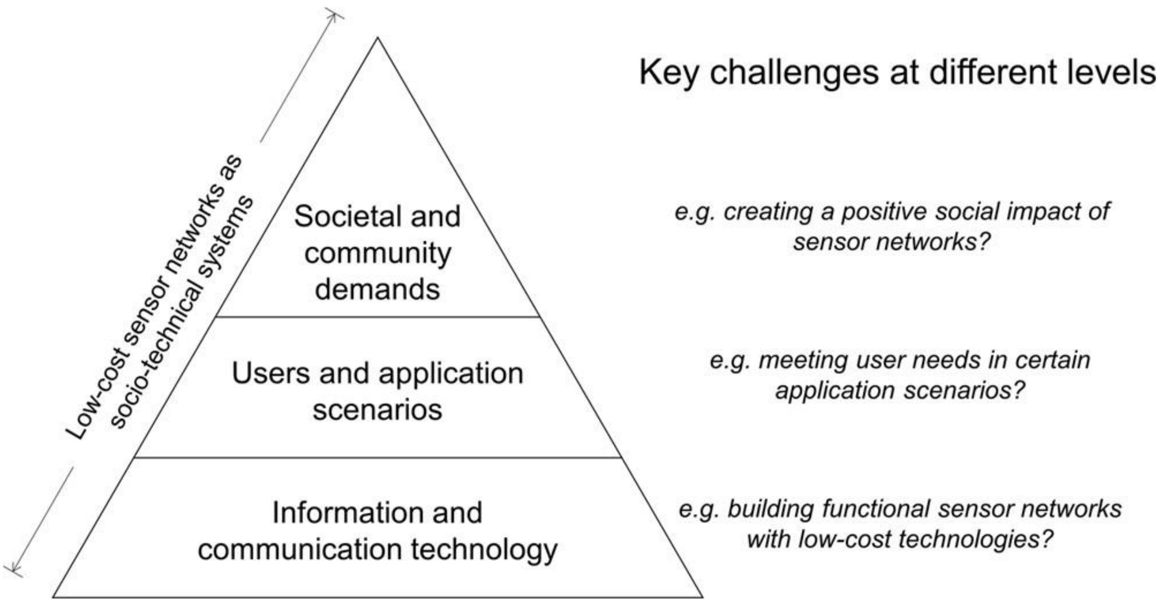
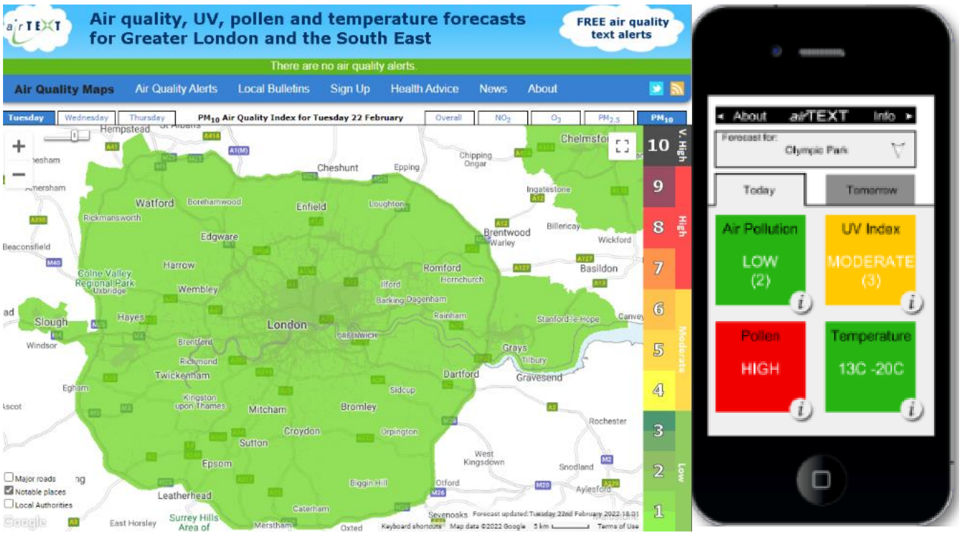


Figure 7. Low-cost sensor networks as socio-technical systems and example challenges at different levels

Local councils, the Greater London Authority (GLA) and National Government, are the organisations that set the wider policies that aim to improve air quality.

Several websites and Apps can look up walking / cycling routes, many with air pollution information as follows.

- Cross river partnership (pictured) Clean Air Route finder - https://www.cleanairroutes.london/
- Clean Air route finder - ***https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/clean-air-route-finder***
- TfL walking routes and Walking App (pictured) - ***https://tfl.gov.uk/modes/walking/ and https://www.gojauntly.com/blog/2018/11/28/go-jauntly-version-2?intcmp=56645&intcmp=56822 (App)***
- AirText alerts about high pollution events (esp. important for asthmatics)



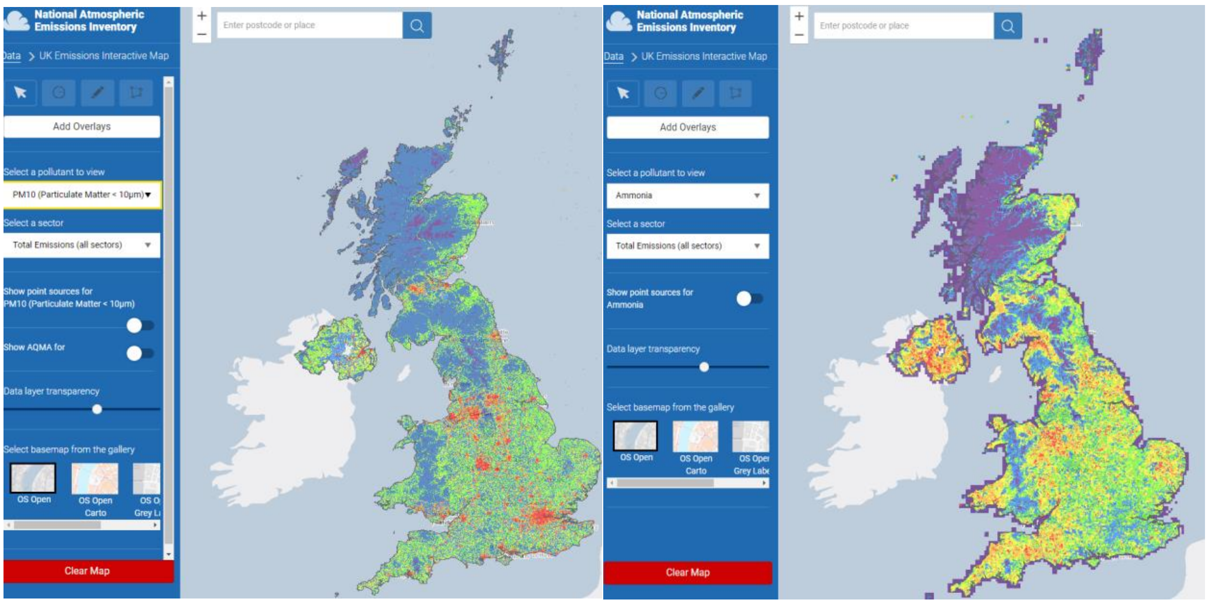
- Air Quality Consultant | Air Quality Assessments | FAQ (***gemairquality.co.uk***)

Air pollution causes chronic inflammation (Araujo, 2011; Midouhas, 2019; Chen, 2012). Inflammation is the body's response to injury and it involves the immune system, and it could be good when you're fighting off a cold or a sprained ankle, but chronic inflammation puts you at risk of many health problems, including cardiovascular and respiratory diseases, cancer.

Oxidative stress occurs when there is an imbalance between antioxidants and free radicals. Air pollution leads to the presence (NO2 is a free radical) or formation (ozone and PM) of free radicals in the body. The free radicals are normally neutralized by antioxidants defence, but when there is a deficiency of antioxidants relative to the radicals, the radicals are left to create damage in neighbouring cells.

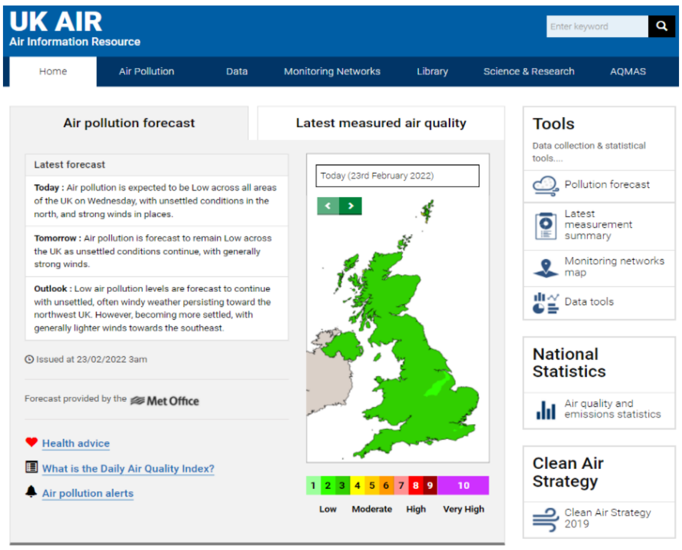
A few more interactive tools available:

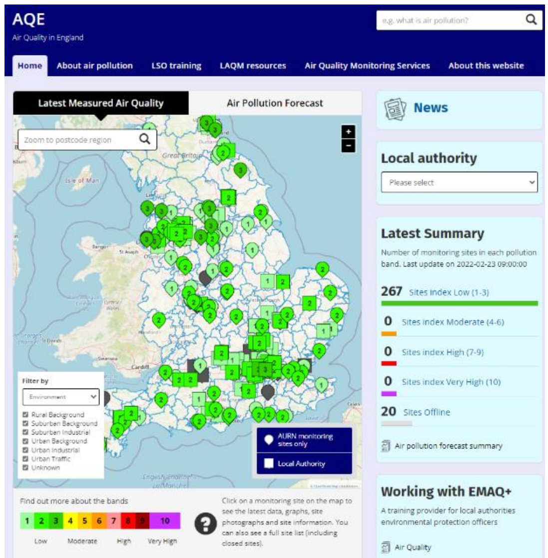
❖ Links: ***https://naei.beis.gov.uk/emissionsapp/*** UK emission interactive map - mapping different pollutants such as arsenic, benzopyrene, benzene, 1,3-butadiene, benzo[b]fluoranthene, black carbon, benzo[k]fluoranthene, cadmium, chromium, carbon monoxide, carbon dioxide, copper, dioxins (PCDD-F), hydrogen chloride, hexachlorobenzene, indeno[1,2,3-cd]pyrene, lead, mercury, methane, nickel, non methane VOC, nitrogen oxidase as NO2, nitrous oxide, PM10 (particular matter <10µm), PM2.5, PM1, PM0.1, polychlorinated biphenyls, selenium, sulphur dioxide, vanadium, zinc.



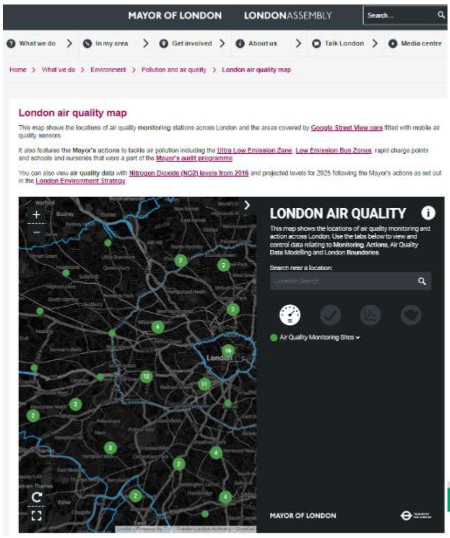
https://uk-air.defra.gov.uk/ Air pollution forecast & latest measured air quality

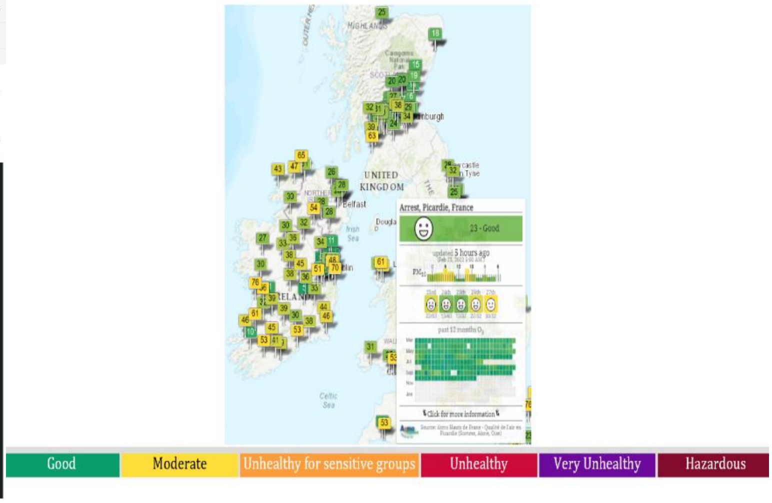
https://aqicn.org/map/unitedkingdom/ real-time air quality index visual map



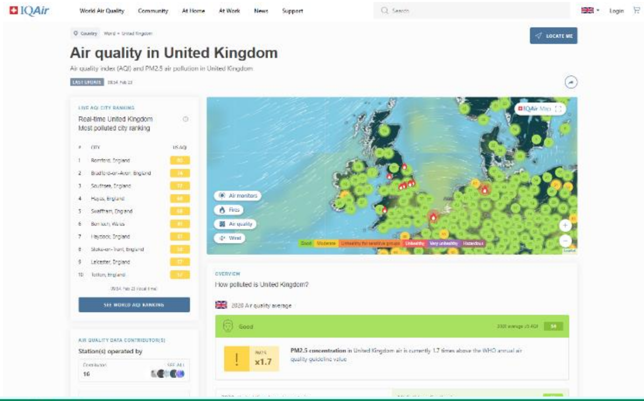


https://www.airqualityengland.co.uk/ Latest Measured Air quality & air pollution forecast

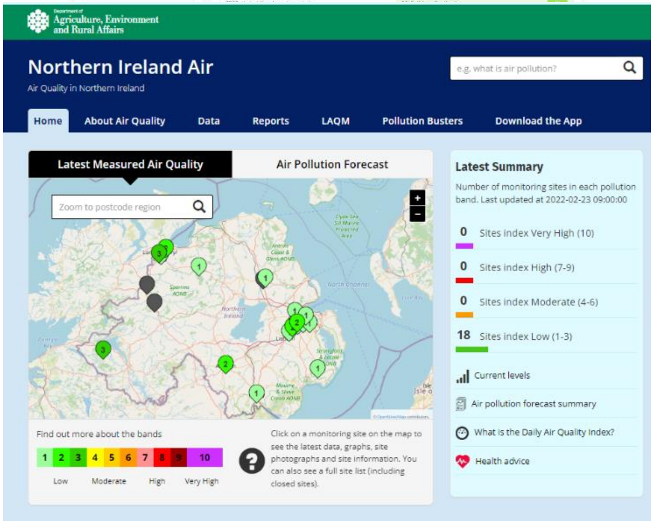




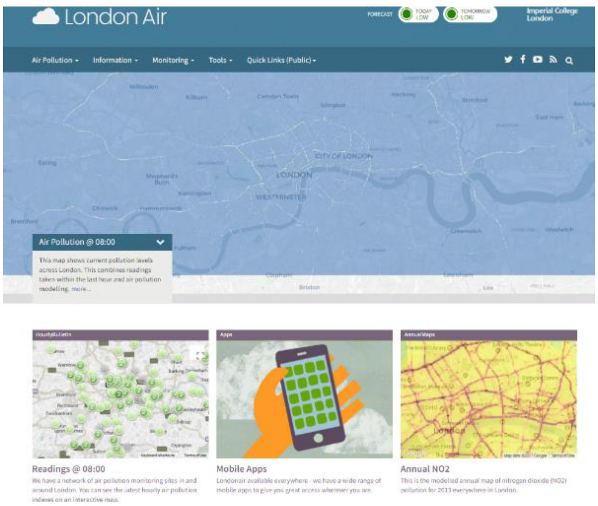
https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/london-air-quality-map London Air quality map *https://www.iqair.com/uk* interactive map



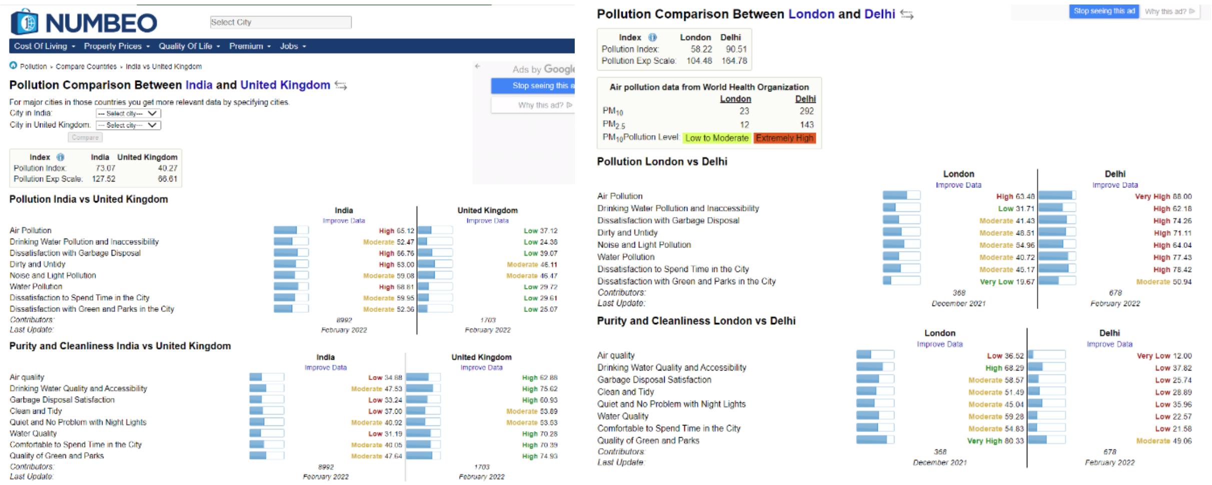
https://www.airqualityni.co.uk/ Northern Ireland Air Quality mapping



https://www.londonair.org.uk/LondonAir/Default.aspx London Air quality network



Pollution Comparison Between India and United Kingdom (numbeo.com) website



There are some ongoing research collaborations using development of AI, data science to understand and improve air quality over London Home | The Alan Turing Institute.

News

Hidden air pollutants on the rise in India and UK

29th April 2021
https://www.ucl.ac.uk/news/2021/apr/hidden-air-pollutants-rise-india-and-uk

Researchers analysed satellite data to estimate trends in a range of air pollutants for 2005 to 2018. Four cities were considered, all at distinct development stages and at various stages of implementing air quality policy: London and Birmingham in the UK and Delhi and Kanpur in India.

Findings of the study:

- The international team of scientists from Belgium, India, Jamaica, and the UK found increases in $PM_{2.5}$ in Kanpur and Delhi. The increases in $PM_{2.5}$ in Kanpur were both significant and substantial, at 3.1% per year. The researchers speculate that these increases are due to increasing vehicle ownership and industrialisation.
- The researchers also found increases in the air pollutant formaldehyde (formed from chemicals collectively known as non-methane volatile organic compounds or NMVOCs, formaldehyde is an ideal marker for NMVOCs emissions). A significant rise

in formaldehyde was detected in Delhi, and a recent sharp increase in London of 9% per year from 2012 to 2018.

- Contribute to the rise in formaldehyde levels in India: vehicle emissions of NMVOCs.
- Contributing to the rise in formaldehyde levels in the UK: NMVOCs emissions from the food and beverage industry, personal care and cleaning products and a range of other household sources (as cars are relatively small sources of NMVOCs due to air quality policies in place in the UK).
- In London, levels of $PM_{2.5}$ and NO_2 were found to be decreasing, whilst all air pollutants included in the study were found to be in decline in Birmingham. For both cities, the declines in NO_2 and $PM_{2.5}$ were significant, with the researchers noting that this reflects the success of policies targeting these emissions sources.

Researchers highlights:

- Importance of satellite data from space-bases instruments to help derive long-term pollution trends to monitor emissions and inform policies to reduce pollution, with their results confirming that vigilance and urgent action are needed across the globe to reduce air pollution levels
- Satellite observations contribute to the tracking of seemingly invisible pollutants; a long and consistent record of observations is vital for assessing the success or inadequacies of current mitigation measures
- Satellite tracking provides useful information about air quality trends and is most useful in cities with limited surface monitoring capabilities.
- It was a surprise to see the increase in formaldehyde above Delhi, Kanpur and London. VOC's might be changing their consistency, potentially driven by economic development and changes in domestic behaviour. It just emphasises the need to monitor our air for the unexpected, and the importance of ongoing enforcement of measures for cleaner air.

Tell motorists to help tackle London's toxic air peaks, authorities urged – air pollution

14th January 2022

https://www.theguardian.com/environment/2022/jan/14/tell-motorists-to-help-tackle-london-toxic-air-peaks-authorities-urged

Campaigners have called on the government to urge people not to drive or light wood-burning stoves during toxic air peaks rather than telling the vulnerable not to exercise or go outside. London suffered its worst air pollution since 2018 on the 14th January 2022, when experts predicted it would reach "band 10", the highest level on the pollution scale.

- The government issued warnings and advised older people and those with lung or heart problems to avoid strenuous physical activity. Even healthy people were told to "reduce physical exertion, particularly outdoors, especially if you experience symptoms such as a cough or sore throat".
- Air pollution campaigners, however, said it was unacceptable to impose more restrictions on elderly or unwell people rather than address the sources of pollution.
- Jemima Hartshorn of Mums for Lungs said: "Londoners are facing the highest pollution episode in years. It has been known for days that today would be very bad for health and what we need is a clear call to every Londoner not to drive, idle vehicles or burn wood.
- The Department for Environment, Food and Rural Affairs, which put out this week's guidance, declined to comment when asked to respond to the campaigners' calls.

Bees: Air pollution prevents pollinating insects from finding flowers

21st January 2022

https://www.bbc.co.uk/newsround/60070824

A new study shows visits to flowers by pollinators were more than 80 per cent lower where pollution was present. Scientists from the University of Reading, the UK Centre for Ecology & Hydrology, and the University of Birmingham believe the pollution interferes with the insect's ability to sniff out flowers. In the study, the researchers used a device which released this type of pollution into an open field. The team then observed the impact this level of air pollution had on the plants. A past study by Reading University scientists has also shown that diesel fumes can change how flowers smell.

This new study suggests that pollution could contribute to the ongoing decrease in pollinating insects, by making it harder for them to find their food - pollen and nectar. Researchers say the study shows how much food production and the natural environment can be affected by pollution.

Gaps identified

Current challenges and developments were discussed during the ongoing interviews:

1. Professor Kirk Martinez highlighted a challenge to the reproducibility and reliability of tests when the research and development project comes to an end, since often after the end of the project, it becomes a challenge to ensure the continued functioning of the sensors long term.
2. Sensors are often only as good as the data sets and models that underpin their function and analysis. Professor Theo Damoulas suggested that gaps can be

found in the modelling of sensors, forecasting interpretations and understanding of relationships between data and the associated analytics.

3. "Low-cost" environmental sensors often come at a price: Professor Firat Guder believes that the gaps for air quality monitoring involve the "trading" off between high performance versus sensor portability and ease of deployment. Developing new more reliable sensors that offer high performance and usability benefits is a gap that many researchers and SMEs are looking to fill. Al

Conclusion

To conclude, air pollution represents a serious public health issue for all living beings and ecosystems and this remains the case in the UK. Air pollution research contains a broad spectrum of expertise, from the primary understanding of environmental processes to monitoring and addressing the root of the issue. There are still a lot of unknowns on how air pollutants combine or interact with each other. Researchers are now aiming to use real-time emissions monitoring to generate a more details picture of real-world emissions. Once the scientific community has the needed data, laws can be updated with the goal of reducing emissions. Low-cost environmental monitoring sensors are ideal for this job since they will be able to provide local authorities with detailed data on air pollution hotspots, thus enabling the creation of more accurate air quality reports.

India

Introduction

According to the WHO, each year, air pollution is responsible for nearly seven million deaths around the globe. Nine out of ten human beings currently breathe air that exceeds the WHO's guidelines for pollutants, with those living in low- and middle-income countries suffering the most. Car emissions, chemicals from factories, dust, pollen and mould spores may be suspended as particles. Ozone, a gas, is a significant part of air pollution in cities. When ozone forms air pollution, it is also called smog. People with heart or lung disease, older adults and children, are at greater risk from air pollution. Air pollution is not just outside - the air inside buildings can also be polluted and affects health.

Pollutants of concern

Particulate matter (PM):

Particles with a diameter of 10 microns (PM10) and 2.5 microns (PM2.5) are inhalable into the lungs and can induce tissue damage, lung inflammation, asthma, chronic obstructive pulmonary disease (COPD), and other adverse health effects depending on long term (months to years) or short-term exposures (up to 24-hours duration). PM can adversely affect ecosystems, including plants, soil, and water, through deposition of PM and its subsequent uptake by plants to alter their growth and yield or its deposition into the water, affecting water quality and clarity. Figure 8 depicts the different source of PM2.5.

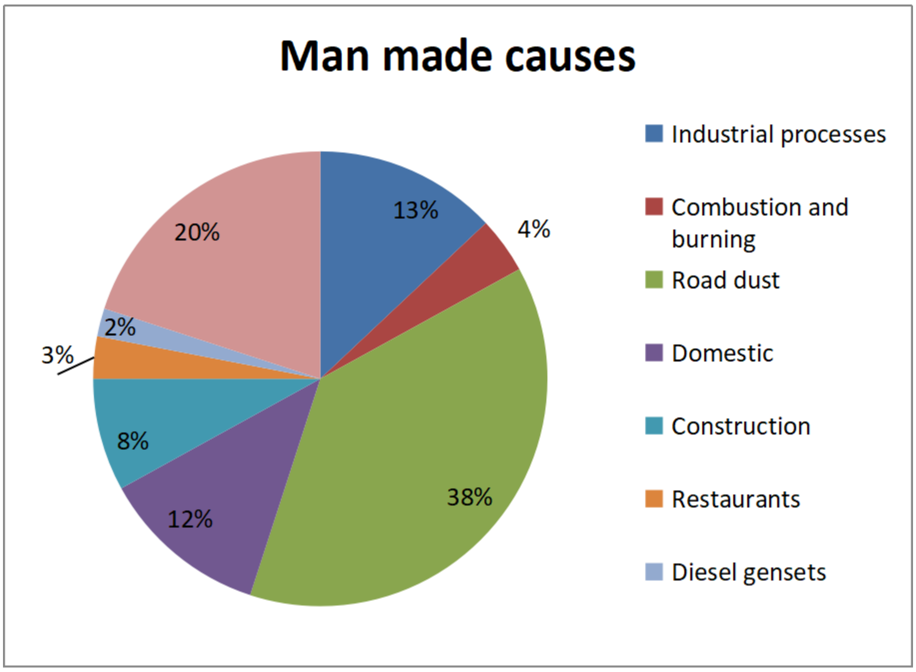


Figure 8. Venn diagram showing the source of PM2.5

The percentage of locations exceeding NAAQS for PM in India are shown in Figure 9.

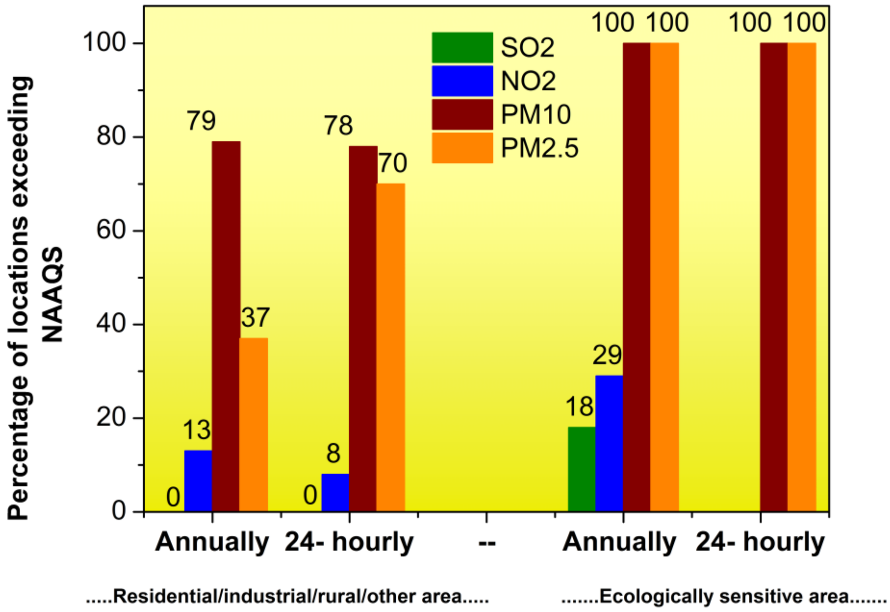


Figure 9. Percentage of locations exceeding NAAQS (annually and 24-hourly)

Nitrogen Dioxide (NO2)

The official limit on the amount of this pollutant considered safe to breathe, the national ambient air quality standard for NO_2, has been set by EPA at 53 parts per billion (ppb), averaged annually and Occupational Safety and Health Administration (OSHA) standard. Guidelines for health and safety recommend that humans should not be exposed to greater than 3 ppm of NO_2 for more than 8 h or >5 ppm of NO_2 for more than 15 min (Becker, 2000). At levels higher than 1 part per million (ppm) in air, NO_2 and NH_3 can cause severe damage to human respiration systems and lung tissues.

Ammonia

Ammonia is a nitrogen and hydrogen complex with an NH_3 formula. It is a colourless and toxic gas with a distinctive pungent scent. NH_3 is commonly produced from vehicles' emitted gases, explosions, and chemical plants. NH3 is extensively used in many areas, such as fertiliser manufacturing, plastics, clinical diagnosis, petrochemical, food processing, and related factories, being one of the most highly produced inorganic chemicals. Severe health issues such as ulcers, liver diseases can be caused by exposure to a high amount of NH_3 gas, and sometimes effects on the human body such as throat, eye, skin, and respiratory irritation. Concentrations above the 25-ppm level in the air are highly hazardous for the health of the human being (Farea, 2021). The chemical industry produces NH_3 for fertilisers and their use in refrigeration systems. The total emission of NH_3 from combustion is about 2.1–8.1 Tg/year (Timmer, 2005).

Hydrogen Sulfide (H2S)

Hydrogen Sulfide is an air-heavier, poisonous, highly corrosive, and colourless gas. H_2S gas is often produced in septic or bacterial sewage systems during the degradation of organic matter, such as animal and human waste. Exposure to H_2S concentrations leads to blood poisoning respiratory system effect. The harmful concentration of H_2S to life is 100 ppm, according to the National Institute for Occupational Safety and Health (NIOSH), and the permissible exposure limit (PEL) is 10 ppm for a maximum period of 10 min (Farea, 2021).

Carbon monoxide (CO)

Carbon monoxide is a colourless, odourless gas. It is produced by incomplete combustion of fossil fuels-gas, from automated vehicles, aircraft, the wood used in boilers, natural gas emissions, coal, mines, gas fires, industrial waste, sewage leaking, solid fuel appliances, water heaters, open fires, and other natural activities, substances on the Earth's surface. Due to the rising amount of CO emissions per year, a large part of CO emissions derives from the exhaust of motor vehicles. The formation of O_3 results from the interaction of CO with sunlight, which is believed to be toxic to plants, animals, and the respiratory system of humans because of its strong oxidising activity. The OSHA has set a limit of 35 ppm of CO in workplaces where a person can be continuously exposed to gas (Farea, 2021).

Table 21 gives the overview of the threshold limit value (TLV) of the air pollutants:

Detection methods

Table 21. An overview of the TLV of environmental hazardous gases

Gas	Release source	Toxicity	TLV
NH_3	Decomposition of manure of animals	Irritation to the eyes at concentrations in the 20-50 ppm range	35 ppm
NO_2	Incomplete air combustion, transport, industrial sector	Respiratory system effected such as chronic bronchitis	3 ppm
H_2S	natural sources such as crude oil, hot springs; Food processing, cooking ovens, craft paper mills, tanneries, petroleum refineries	Breathing system	10 ppm
CO	Incomplete combustion of fossil fuel gas, automated vehicles, oil, aircraft, open fires, industrial waste, natural gas emission	Reduction in oxygen intake into the bloodstream leading to organ dysfunction	35 ppm

Sensor based technique for Air Quality Monitoring - Indigenous R&D

Some of the indigenous research in different universities for air pollutants has been tabulated in Table 22. More details on the sensors are available in Annex III.

Parameter	Sensing technique	Chemistry	TRL	Sensitivity and response time	Dynamic range	Recovery time	Reference
Nitrogen Dioxide (NO_2)	FET (High electron mobility)	Pd-AlGaN/GaN-NO_2	3	91.6 % and 9s @ 300°C, 100 ppm	10 to 100 ppm	48s @ 100 ppm	(Nguyen, 2021)
	FET (Capacitive)	Si MOSFET-NO_2	3	44.6% and 107s @ 180°C, 0.5 ppm	0.25 ppm to 2.5 ppm	417s @ 2.5 ppm	(Hong, 2020)
	Thin film transistor	MoS_2-NO_2	4	0.5% for 1 ppm and 10s @8 ppm	1 to 256 ppm	5s @ 8 ppm	(Kim, 2020)
	Electrical (resistance)	Graphene-Au nanohybrid-NO_2	3	3.2 % and 135s @ 50 ppm	50 ppm to 200 ppm	136s@ 50 ppm	(Rattan, 2022)
	Chemiresistive	ZnO/rGO-NO_2	3	13.46s @ 2 ppm	5 ppb to 10 ppm	164s @2 ppm	(Chen, 2021)
	Resistive	WO_3-N-GO-NO_2	3	46% and 90 s @ 200 ppm@ 200 °C	50 ppm to 300 ppm	205s@200 ppm	(Badiezadeh, 2021)
	Conductance	SWCNT-TiO_2-NO_2	4	2 min @ 25 ppm	12 ppm to 40 ppm	5 min@ 25 ppm	(Panzardi, 2020)
	Conductance	3D SiO_2 MWCNT NO_2	3	82.61 % and 1450s@ 1 ppm	50 ppb to 50 ppm	44s@ 1 ppm	(Ma, 2020)
	Resistive	CoPc–COOH-NO_2	3	100s@50 ppm	50 ppb to 50 ppm	100s@50 ppm	(Jiang, 2020)
Ammonia (NH_3)	FET (organic)	DPP-T-TT-NO_2	4	5 min	2.17 ppb to 200 ppm	30 min	(Mougkogiannis, 2021)

	Capacitive	SiC FET-Pt -NO_2	3	-400 mV and 500s @ 29 ppm	29 ppm to 290 ppm	1000s @ 29 ppm	(Y. Sasago, 2020)
	Resistive	Au-MoO_3-WO_3-NH_3	3	5 min@5 ppm	1 to 50 ppm	10 min@ 5 ppm	(Xu, 2000)
Hydrogen Sulfide (H_2S)	FET	IGZO-H_2S	3	5s@ 250°C, 50 ppm	10 ppm to 130 ppm	100s@50 ppm	(Shin, 2021)
	FET (Chemical)	ZnO-Au-Pt-H_2S	3	4400 ppm^{-1}, 8s@ 1 ppm	60 to 180 ppb	8s@ 1 ppm	(Kaiser, 2020)
	FET (Chemical)	NBR-TOA nitrate-H_2S	4	53 mV/10^{-1}, 120s@34.1 ppm	170.5 to 17050 ppm	120 s @ 34.1 ppm	(Sherbow, 2021)
	Chemiresistive	CNTs/SnO_2/Cu-H_2S	3	4.41, 4 min@80 ppm	10 to 80 ppm	10 min @ 80 ppm	(Zhao, 2020)
	Chemiresistive	$C_{60}Br_{24}$/ SWCNT - H_2S	3	1.75 % @ 50 ppb	50 ppb to 1 ppm	25 s@50 ppb	(Zhou, 2021a)
	Resistive	PDNS-SWCNT-H_2S	5	10 min @ 25 ppb	25 ppb to 1 ppm	30 min@ 25 ppb	(Zhou, 2021b)
	Conductance	PAni-$SnCl_2$-PEDOT:PSS-H_2S	4	100s@167 ppb	50–1000 ppb	100s@167 ppb	(Duc, 2021)
Carbon Monoxide (CO)	Chemiluminescence	Au/Nd_2O_3 – $Ca_3Nd_2O_6$-CO	3	0.03s@ 131.63 °C, 10 ppb	0.6–125 ppb	0.04s@10 ppb	(Zhang, 2020)

Table 22. Indigenous R&D in chemical water quality sensors

Many universities across India have been working to produce low-cost sensors for air quality monitoring, with collaborations with foreign universities, companies, or funding agencies. Some of their research has been deployed in various regions for pilot studies to collect data and validate the sensor result with standard methods. Some of these sensors have been tabulated in Table 23.

Table 23. University/company/funding agencies collaboration sensors for air quality

Company	Sensor	Picture	Cost	Portable	TRL level	Advantage	In field	Parameters	Technical specification link
CERCA, IIT, Delhi	Aerogram, Sound based hybrid approach		< ₹.8000	Yes	7	• Large spatial coverage • Low cost • Accurate	Yes	PM	https://cerca.iit.ac.in/app/assets/images/events/Q1%20Report%202020.pdf
IIT, Madras and DST	Wearable sensors		₹3.32 lakh	Yes	7	• Simple • Low-cost • Easy handling • Battery operated	Yes	NO_2, CO, temperature and humidity, CO_2, ozone, noise	https://www.biospectrumindia.com/news/58/18566/iit-m-uk-researchers-develop-paper-based-sensor-to-detect-antimicrobial-pollutants.html

CERCA-Centre of Excellence for Research on Clean Air

Commercial air quality collaboration sensors

The University/company/funding agencies' collaboration sensors have been mass-produced and are replacing the standard expensive ones to give better control over the air quality. These sensors are tabulated in Table 24.

Table 24. Commercial level sensors developed by universities/ company/funding agencies' across India

Company	Sensor	Picture	Cost	Portable	Advantage	In field	Parameters	Technical specification link
Indian Institute of Technology, Kanpur (IIT-K)	Light scattering technology-Adopted in Mumbai, MPCB		₹ 50,000 to Rs. 2 lakh	Yes	Automatic monitors providing real-time data that is easy to interpret	Yes	PM10, PM2.5, ozone, NO_x, SO_x	https://www.hindustantimes.com/india-news/mumbai-gets-sensor-based-monitors-as-low-cost-air-monitoring-feasibility-study-begins/story-LjSYWRqLsC7Q27B6WQDrEN.html
CPCB	Air Quality Monitoring Station		₹ 1.5 crore	Yes	• Portable • GSM enabled • Auto calibration unit	Yes	CO, NO_2, SO_2, O_3, PM10 & PM2.5	https://www.cdac.in/index.aspx?id=pdf_Air_Pollution_Monitoring

Recent advances in sensing techniques

Government organisations such as DST and APCTT are working towards the improvement of air quality by supporting R&D activities. Some of the projects that they have initiated are explained in this section.

Indigenous Air Unique-quality Monitoring (AUM) Photonic System developed for Real-Time Remote Monitoring of Air Quality

WHO’s reports show that the worsening state of air quality is responsible for more than 7.5 million fatalities worldwide annually. This highlights the necessity for accurate, yet cost-effective monitoring of air quality parameters as monitoring is critical to solution. The current systems and technologies used for air quality monitoring are prohibitively expensive for wider deployment. This underlines the need for development of systems for real-time remote monitoring of relevant air quality parameters. With the support DST's Clean Air Research Initiative, Prof. Rao Tatavarti, Director of Gayatri Vidya

Parishad-Scientific and Industrial Research Centre (GVP-SIRC) & GVP College of Engineering, Visakhapatnam, with other partners have developed an indigenous Air Unique-quality Monitoring (AUM) photonic system for real-time remote monitoring of air quality parameters. It has been found to be highly sensitive and accurate and capable of simultaneous detection and quantification of all air quality parameters and offers a number of merits over any of the currently available conventional systems. It is portable, compact, low powered and economical, works on plug and play system, requires no setting uptime, and no additional civil infrastructure for housing. AUM was successfully evaluated during laboratory trials with gold standards (in collaboration with EffecTech, UK), and also compared in the field with imported systems from France, and Australia and operated by Karnataka State Pollution Control Board under the aegis of the Central Pollution Control Board of India.

DST's initiatives tackle air pollution hazard

Air pollution in India is a serious issue, ranking higher than smoking, high blood pressure, child and maternal malnutrition, and risk factors for diabetes. At least 140 million people breathe air 10 times or more over the WHO safe limit and 13 of the world's 20 cities with the highest annual levels of air pollution are in India. The common sources of air pollution are household pollution, motor vehicles, industrial facilities and forest fires. It is responsible for the exacerbation of asthma and the increase in respiratory infections, especially in children. Increased morbidity and mortality, due to cardiovascular diseases including stroke, chronic respiratory diseases and cancers have also been attributed to air pollution.

The DST department has supported to develop Wind Augmentation and Air Purifying Unit (WAYU) devices that can be positioned in an industrial complex, residential complexes, and schools in the vicinity of traffic road intersection/divider to tackle dust pollution. At such places, a significant amount of pollutants are emitted. It aims at removal of such pollutants which are ejected by the vehicles in the traffic. It allows reducing ambient air pollution levels at places, which have high concentration of pollutants. WAYU can reduce PM10, PM2.5, Carbon monoxide (CO), volatile organic compounds (VOCs), hydrocarbon (HC) emitted in the atmosphere working basically on two principles mainly Wind generation for dilution of air pollutants and Active Pollutants removal (filters, activated carbon and UV lamps). A prototype has been installed at ITO Intersection and Mukarba Chowk. The device consumes a half unit of electricity each day for running for 10 hours each day. The cost of the device is Rs.60,000 per device. Maintenance cost is Rs.1500 per month.

The other technologies are in the process like Traffic Junction Air Pollution Abatement Plan; Landfill Fire Control Mechanism through integrated approach; Collecting Particulate Matter (PM) in air using filters placed on the top of a moving car; Suddha Vaayu; an electrical chamber for detection and mitigation of air pollution etc.

Clean Air Research Initiative (CARI)

DST initiated a solution-oriented R&D activity for mitigation of Air Pollution. The Programme focuses to identify the technologies that can provide viable deployable solution to mitigate the air pollution and to establish technical resource unit. The programmes include Traffic Junction Air Pollution Abatement Plan, Landfill Fire Control Mechanism through Integrated Approach, Suddha Vaayu: An Electrical Chamber for Detection and Mitigation of Air Pollution, Collecting Particulate Matter in Air Using Filters Placed on the Top of a Moving Car, Indigenous Photonic System for Real Time Remote Monitoring of Air Quality and, Mitigation of Air Pollution: Micro-to-Macro Scale Study of Particle Capture by Liquid Droplets. As air pollution comprises of smoke, dust and haze which can be collectively named as aerosols which defines suspension of small particles in air. The fundamental aim of the liquid droplet project is to study of particulate matter (PM) capture efficiency by single droplet using two techniques of electrostatic charging of droplet and/or aerosol and addition of additives based on chemical characteristics of the aerosols.

APCTT

Some of the projects handled by ESCAP are shown in Table 25.

Table 25. Projects handled by ESCAP

Project details	Extract
Environment and Development Promoting transformative actions for sustainable development in the region	At the Environment and Development Division, our workplan is designed strategically around five thematic areas: 1. Raising Climate Ambition 2. Safeguarding Ecosystems' Health 3. Protecting the Ocean 4. Climate Change and Air Pollution 5. Cities for a Sustainable Future In addition to these thematic areas, we mainstream cross-cutting issues in our lines of work. In particular: 1. Green Growth, and 2. Strengthening Environmental Governance
Air Pollution and Climate Change: ESCAP supported by the Republic of Korea	Enable cities to make evidence-based decisions to reduce urban air pollution. These analytical efforts have utilized machine learning to demonstrate that the primary causes of air pollution vary significantly among urban centers, even in the same country and region. Using data-science-based evidence, this program aims to enable policymakers in project cities to make planning decisions that effectively tackle air pollution for resilient and sustainable urbanization and economic development. EDD also intends to work with stakeholders in pilot cities to develop action plans to improve air quality situations locally and for all individuals living in the region.
Safeguarding ecosystems' health	EDD support a transition to agro-ecology in Asia and the Pacific, as an example of low carbon, risk-informed, resilient, regenerative and sustainable agricultural practices, which apply ecological principles to food systems. A regional push to support the transition towards agro-ecology in Asia and the Pacific would support environmental progress in the region, in line with the principles of planetary health.

Gaps Identified

1. The current experimental systems for air pollutants health impact evaluation are implemented without considering their realistic exposure doses and periods. These results therefore may pinpoint the mechanisms responsible for observed toxic effects but cannot predict their long-term effects under environmental exposure scenarios. Under this setting, future work should aim to illustrate the bio-risk of air pollutants under more realistic environment conditions.

2. A lack of detailed, highly time-resolved air quality data and an insufficient understanding of atmospheric chemistry make it difficult to carry out adequately detailed source apportionment. For example: Research regarding toxic effects of pollutants that are adhered on PMs with studies related to their release from particles in biological system, as well as their individual toxic effect and their transformation under biological conditions needs to be studied. Obtain more accurate air quality data and atmospheric chemistry information with both higher spatial resolutions to better understand, for example, pollutant concentrations in microenvironments and an individual's personal exposures and temporal frequency to better understand acute and chronic exposures.

3. Improved atmospheric sciences information needs to be tied to specific cardiovascular and respiratory health endpoints through toxicological and human panel studies and population-based epidemiological studies. For example, the issue of transmission of pathogens through air pollutants, especially PMs and aerosols, in the atmosphere as well as the indoor environments is underestimated and needs more study.

4. It is important to obtain more data concerning health impacts with larger population and to bridge the knowledge gaps between the findings and laboratory mechanistic studies of the air pollutants. The availability of relevant data on the subject continues to be a challenge to the research community and policymakers. A parallel deficiency exists in human panel studies of susceptible people to ambient air in different airsheds dominated by different sources.

5. Few studies have been published that provide firm evidence of causal relationships between components or emissions and their associated health effects to help guide policymakers and regulators in making better informed decisions regarding emissions reductions. There is uncertainties and gaps in existing management policies and control strategies. There is a need for policymakers and regulators for adequately managing air quality by paying crucial attention to least studied regions and domains and offering a strategically planned pathway for air quality management, considering the future national scenario by adopting a holistic approach to manage the increasing

air pollution and should not be limited to a research study that highlights the sources and their contribution.

6. Developing emission inventories only at metro scales would not bring the intended results as emissions have no boundaries. Henceforth, it is imperative to employ a transformative approach that quantifies cross-border pollutant specific loads in urban or rural areas.

7. For population-based epidemiology, serious thought should be given to using concentrations of several different pollutants modeled to areas near the subjects' homes and assessing how risk estimates of the different pollutants change rather than using concentrations from central monitors to express exposure across a wide area.

8. In addition, the air quality manager should closely work with the enforcement agency to properly implement the suggestive actions and measure the effectiveness of the implemented control actions after 1–2 years.

9. There is a significant gap in sensor manufacturing in India. While a wide variety of sensors with good efficacy are being fabricated and their performance is proven in labs, there is a minimal effort in large scale sensor manufacture at the industrial level. For example, there is no commercial sensor indigenously manufactured for PM. The sensor market of about 200 Million $ presently is expected to grow to about 1 billion $ very soon. Indigenous manufacture of different sensors is to be undertaken with utmost priority to reduce the dependence on sensors from other countries, mainly to tackle the non-availability of sensors. In addition, good calibration facilities are required for different environmental sensors.

Highlights from interviews with people of interest and stakeholders

The UK team of researchers working on this project had the opportunity to interview several people of interest with high level of expertise in the subject of low-cost environmental monitoring sensors, such as academics, industry partners and policy makers. From the academics contacted, Professor Kirk Martinez and Professor Theo Damoulas gave their point of view regarding the subject of machine learning and AI useful for the communication within sensor networks, Dr Firat Guder gave his point of view as academics working in related areas, and Nicholas Davies and Professor Alastair Lewis shared their point of view related to policy makers around the subject of pollution monitoring.

Prof. Tripathi and his team from, IIT Kanpur have developed a network of indigenous/imported sensors instead of expensive air quality monitoring systems. PM sensors have been deployed with reliable data collection at 40 different locations in Jaipur, with R-squared better than 0.75 and error less than 10 %. Extensive field evaluations have been made for more than 7 months. In addition, sensors have been deployed in 15 locations across the country, with reliable data collection, with R-squared better than 0.85 and error less than 15 %. The deployment cost is around ₹ 2-3 Lakhs, with almost 60 % cost reduction. Other advantages of sensor-based systems are, small form factor, Wi-Fi/4G enabled, solar powered and only requiring a small area. They generate about 15 times more data with much higher speeds. The main issues/disadvantages in sensor-based air quality monitoring units are comparatively less accuracy, precision, and stability.

Prof. Bharadwaj Amrutur, IISc, Bangalore and team, have developed low-cost gas sensors for environmental monitoring. The aim was to create a smart fusion of a large number of low-cost sensors and couple them with a few high-quality and high-cost sensors and develop data fusion techniques to achieve an affordable cost and acceptable quality for sensing for public respiratory-health related use case.

The investigators have designed and developed novel molecular architectures and fabricated a solid-state sensing device for explicitly detecting a variety of analytes like VOC, nitrates, heavy metals like lead, mercury, and chromium ions, as well as iron, fluoride, arsenic ions, and biological organisms such as E. Coli. The most important aspect of the research is decoding and elucidating the interaction between sensing molecules and analytes.

The complete details of the interviews are given in Annex I.

ANNEX I- Interviews

Name	Expertise	Position
Dr Firat Guder	His research primarily involved investigation of nano structural transformations by atomic layer deposition, unconventional methods for photolithography and patterning, synthesis of nanomaterials and design and fabrication of sensors and actuators. Featured article: "Low-cost intelligent soil sensors could help farmers curb fertiliser use"	Senior Lecturer Faculty of Engineering, Department of Bioengineering Imperial college London
Prof Kirk Martinez	Design and build environmental sensor networks specialist	University of Southampton
Prof Theo Damoulas	Machine Learning and Data Science specialist	University of Warwick
Nicholas Davies	Manage and research influential inquiries for the cross-party Environmental Audit Committee on issues such as green finance, sustainable fashion and water quality in rivers.	Senior Committee Specialist with the Environmental Audit Committee, House of Commons
Professor Alastair Lewis	Alastair works extensively with government on air pollution policy, and is a member of the Defra Air Quality Expert Group, and has provided evidence to House of Commons select committees on this subject. He also works with industry translating atmospheric chemical technologies into other fields. Recent collaborations include joint research projects with Markes International, the National Physical Laboratory, DSTL, Givaudan UK, Anatune Ltd and AWE plc	Professor of atmospheric chemistry at University of York & Chair of the DEFRA air quality expert group
Prof. T Renganathan	The areas of expertise are Hydrodynamics of multiphase systems, Analysis of gasification processes and Inertial and paper-based microfluidics.	Professor, Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai, India

Prof Sachchida Nand Tripathi	Aerosol Science is Prof. Tripathi's chosen field of study. His contributions take a comprehensive science-centred approach to extremely relevant environmental issues such as Low-Cost Sensors for Air Quality Monitoring and air pollution source identification. At the same time, he has taken an interdisciplinary approach, emphasizing the seamless connection between air quality and public health and climate change impacts. A recent article featured in his work "New sensors by IIT-Kanpur to give local data on pollution to residents."	Professor & Head, Department of Civil Engineering, Indian Institute of Technology, Kanpur, India
Prof. Bharadwaj Amrutur	Prof. Bharadwaj has led the creation of a new academic and research program in robotics and autonomous systems. He was also the lead in creating a data exchange framework, which has been realised as the India Urban Data eXchange by the Ministry of Housing and Urban Affairs. Researching ML-driven Robotic Systems is another area. He has broadened the research activities to embrace hybrid systems like CPS and IoT.	Professor, ECE Department, Division of EECS, Indian Institute of Science, Bangalore, India
Prof. Praveen C Ramamurthy	Prof. Ramamurthy's area of expertise is Electroactive polymers, Nanocomposite, Organic nanoelectronics, and sensors. Area of polymer electronics like Schottky diode, FET, OPVD, sensors, with the current focus on the elucidation of the structure-property relationship of polymers to the performance of the devices and functionalization nanocomposites.	Professor, Department of Materials Engineering, Indian Institute of Science, Bangalore, India

Professor Kirk Martinez is a member of the EPSRC, IEEE, did his PhD in Electronic systems Engineering and as Professor in Advanced Computer Networks at University of Southampton, also took part in the *Glacsweb* project as the project leader. He designs and builds complete systems, hardware, software, and algorithmic sensors and his research is focused on Environmental sensor networks, aiming to advance deployable systems while making them AI. Professor Martinez states that one issue regarding climate change is that it is all down to locals and scientists to report events, and low-cost environment monitoring sensors (LEMS) can be helpful by making the reporting of events cheaper and faster, and because of that contributing for the monitoring of pollution in developing countries. The main feature LEMS have is that people can afford to do their research with it without needing to borrow or buy an extremely expensive device, it also covers a bigger area allowing for more measurements to be taken. Having the possibility to have more sensors deployed also means that in the scenario of harsh environment conditions result in the loss of some of the sensors, researchers will still be able to retrieve data from the remaining ones. Additionally, the sensors are smaller and lighter and therefore easier to carry and deploy. Professor Kirk also mentioned that communication is key and is a must that battery life lasts the time needed for the length of the project and the sensor must be able to communicate within reason, at least once a week depending on the project. Current challenges with Low-cost environmental sensors are the reliability and reproducibility of tests, hidden costs, and being able to maintain and carry good function of sensors after the project comes to an end. Professor Martinez believes that funding should be invested in prototype projects using space networks cheap to use and communication through satellites, water monitoring research, mass migration, mass landslides, and in general all climate change and pollution related.

Professor Theo Damoulas is a NERC senior expert in the Constructing Digital Environment with a PhD in computing science about Probabilistic Multiple Kernel Learning, he is also a Professor in Machine Learning and Data Science at the University of Warwick as well as founder and PI of the cross-departmental Warwick Machine Learning Group. His research interests are around probabilistic machine learning and have had broad applications in spatiotemporal problems in urban science and computational sustainability. Professor Damoulas believes the public needs education on the limitations, assumptions, advantages and benefits of AI technology. It is of extreme importance to understand that data is not information, it contains information. This is the part where AI, statistics, mathematical modelling come into play, local sensors, and sensing in general need models to be able to integrate and capture different signal to noise ratios of the quality of the sensor, also need certification of sensors with specification that measurements may not correspond to reality because we do not have a ground truth. The state of the art in terms of modelling air pollution has been focusing on mechanistic models, a mathematical description of the dispersion diffusion process across buildings and across the physical world. Professor Theo believes this new technology differs because it is scalable, transferable to other cities, is data driven and incorporates prior knowledge, physics, causal relationships that can exist in the real world, and it complements the spectrum of approaches that are out there. Professor Damoulas states that there are still gaps in the intelligent decision making with human machine interplay and with science, policy, and public interplay. Challenges to modelling, forecast interpretation and understanding of relationships include being able to track dynamics driven by external factors. Professor Damoulas believes the ladder of research that is needed to develop a product from applied research to really having a product goes a long way. Funding should go to basic research, applied research, cofound with the industry to do the next step, at the same time we need to fund policy makers and local authorities to be able to have the capacity to use technology, train the personnel, and develop systems able to use the technology.

Dr Firat Guder is a senior lecturer at Imperial College London, he completed his PhD at the University of Freiburg. His research includes the investigation of nanostructural transformations by atomic layer deposition, unconventional methods for photolithography and patterning, synthesis of nanomaterials and design and fabrication of sensors and actuators. Dr Guder believes the main advantage of low-cost sensors is that they can create high volumes of data, and ideally do not require trained personnel to operate it, and challenges exist in the performance of sensors and oftentimes high performance can be "traded" by portability and low-cost devices. Dr Guder believes funding should be more invested in the areas of food and environment technology, in seed funding ideas to take them forward, and to empower researchers.

Nicholas Davies is a senior policy specialist in the science and environment cluster of committees in the House of Commons, where his role is to manage and research influential inquiries for the cross-party Environmental Audit Committee about national issues like green finance, sustainable fashion, and water quality in rivers. Nicholas Davies states that water quality became a hot topic in the media the past few years and that the Environment Act 2021 aims to address water pollution issues in several ways, like the requirement for water companies to progressively reduce the number of discharges from storm overflows, and to approve downstream and upstream monitoring on the sewage treatment network. EU strategic policy direction statement has made it clear that water regulators must take tougher action, prioritizing long-term improvements in the network over shorter reductions or keeping the bills down. Therefore, there is an increased need for water quality monitoring deployed by water companies, but current monitoring is patchy, underfunded, outdated and it does not cover most of the pollutants currently affecting rivers. Funding should be invested in the Environment Agency, and it should be down to them to decide where funding should be prioritised.

Professor Alastair Lewis did his PhD at the University of Leeds on hyphenated chromatographic techniques for the analysis of urban and combustion particles, he works in the Wolfson Atmospheric Chemistry Laboratories and is a Professor of atmospheric Chemistry at the University of York. His main area of research is related to air pollution, including combustion emissions, ambient air quality, indoor air quality, development of analytical methods for measurement of pollution and related constitutes. Professor Lewis states that there is clearly an opportunity to improve the way exposure is being assessed, however there are challenges associated with sensitivity and precision of LEMS measurements. Gaps in research include the lack of development of new sensors rather than the improvement of old ones. Currently there is very little research and development on new sensors, mostly due to lack of funding. Grants for the developing of new sensors are hard to get, and government bodies typically do not have an understanding of the roadmap stages and expect a new product to be develop in a short period of time with little costs associated, while in reality it might take years to develop a high precision, genuinely low-cost sensor, and the first one will probably be hugely expensive to produce and achieve. Funding should go towards education of politicians and the public, basic analytical science to develop new products and allow for a novel approach of measurements, more sophisticated miniaturized devices as small compact versions of analytical techniques (mass spectrometry, gas chromatography, absorption instruments, laser induced fluorescence, etc.) that usually produce high quality measurements due to their infrastructure for calibration, framework and specificity.

Prof. T Renganathan did his PhD in Chemical Engineering. His research interests include multiphase systems, gasification and capture of CO_2. Prof. Renganathan and his team from IIT, Madras have developed a low cost, field-deployable colourimetric paper-based microfluidics sensor (LP-μPADs) and adsorptive colourimetry sensor to meet the Affordable, Sensitive, Specific, User-friendly, Rapid and robust, Equipment-free and Deliverable to end-users (ASSURED) criteria set by WHO for the detection of antimicrobials in water bodies as a viable tool for environmental surveillance. Periodic monitoring of antimicrobials and antibiotic-resistant genes is the key to assessing India's current Antimicrobial Resistance (AMR) situation.

Prof. Tripathi is the recipient of Shanti Swarup Bhatnagar Award and the J C Bose National Fellowship. He holds the Arjun Dev Joneja Chair at IIT Kanpur. He is an elected fellow of the Indian National Science Academy (INSA), Indian National Academy of Engineering (INAE) and National Academy of Sciences of India (NASI) and recipient of the Distinguished Alumnus award of Banaras Hindu University. He has made impactful contribution to address challenges of Air Pollution and Climate Change. Prof Tripathi has built ground-breaking innovative approaches for indigenously built low-cost sensor-based network technologies for nation-wide urban air quality monitoring and Real Time Source Apportionment (RTSA). He and his team from IIT Kanpur have developed network of indigenous/imported sensors instead of expensive air quality monitoring systems. PM sensors have been deployed with reliable data collection at 40 different locations in Jaipur, with R-squared better than 0.75 and error less than 10 %. Extensive field evaluations have been made for more than 7 months. In addition, sensors have been deployed in 15 locations across the country, with reliable data collection, with R-squared better than 0.85 and error less than 15 %. The deployment cost is around ₹ 2-3 Lakhs, with almost 60 % cost reduction. Other advantages of sensor-based systems are, small form factor, Wi-Fi/4G enabled, solar powered and only requiring a small area. They generate about 15 times more data with much higher speeds. The main issues/disadvantages in sensor-based air quality monitoring units are comparatively less accuracy, precision and stability.

Prof. Bharadwaj Amrutur is presently Chairman, Robert Bosch Center for Cyber Physical Systems. He got his BTech in Computer Science and Engineering, from IIT Bombay in 1990, MS and PhD in Electrical Engineering from Stanford University in 1994 and 1999. He and his team from IISc, Bangalore, has developed low-cost gas sensors for environmental monitoring. The aim was to create a smart fusion of a large number of low-cost sensors and couple them with a few high-quality and high cost sensors, and develop data fusion techniques to achieve an affordable cost and acceptable quality for sensing for public respiratory-health related use case.

Prof. Ramamurthy received his M.Sc. degree in polymer science from the University of Mysore, Mysore, India, in 1994, and the Ph.D. degree in textile fibers and polymer science from Clemson University, Clemson, SC, USA.He joined the Indian Institute of Science (IISc), Bengaluru, India, in 2007, where he is currently a Professor with the Department of Materials Engineering. His research interests in organic electronics include organic photovoltaics, sensors, and ultrathin EMI shielding films. He and his team from IISc, Bangalore, have designed and developed novel molecular architectures and fabricated a solid-state sensing device for explicitly detecting a variety of analytes like VOC, nitrates, heavy metals like lead, mercury, and chromium ions, as well as iron, fluoride, arsenic ions, and biological organisms such as E. Coli. The most important aspect of the research is decoding and elucidating the interaction between sensing molecules and analytes.

Professor Kirk Martinez – Academic at University of Southampton

1. Please introduce your research. What are the aims?

My main research and goal is related to sensing for earth signs, the use of new technologies particularly communications technologies, to help scientists gather data in better ways. Sometimes with sensors but usually with whole systems, it takes months to get one week worth of data, regarding actual real-world problems and we are trying to tackle that one problem at a time. We have done it for glaciers, and we are doing it for other topics as well. By using new technology as it comes out and is still cheap, satellite imagery, UADS, we just finished a National Geographic project on monitoring environments which are changing so rapidly because of climate change that we need to capture the landforms and things like this before it gets whipped away by water for example, also some new GPS technology.

2. Regarding the development of a low power wireless sensor network capable of surviving several years in harsh environmental conditions, what is so important about this sensor?

In most cases when a scientist wants to monitor things like earthquakes, pollution etc., we face the question "How do I do it?", we usually find ourselves looking at thousand pound machinery options, meaning we must find a way to buy or borrow the item, and maybe we can get 1. This is the most likely scenario in scientific research, and the main feature of the lower cost devices is that you can afford to do your research with it, and you can have more and cover a bigger area. Usually, we lose a few sensors due to the environment conditions, crushing mountains, rivers etc. So, it is good for a scientist to know that they can put these things by a river and in case of a terrible flood, they were still able to recover some data from the remaining sensors, that is one good aspect regarding low-cost sensors. Typically, the lower cost items are smaller as well, making them lighter to carry and deploy. What we also found is that commercial equipment is not so easy to connect to the world, so you can't connect them to the internet so easily, strangely all the cheaper devices tend to connect very easily, and you can remotely access data.

Specialty – communication; make sure that from all the aspects, the sensor has to actually be usable, the battery life of it has to be able to last a whole year if needed, we must be able to communicate within reason, certainly every week.

3. How does this sensor (or sensor network) differ from other types of technology?

It is Cheaper and lighter therefore can use more sensors and achieve better and more reliable results. Easier to connect to access remote data.

4. We just spoke about some of the advantages of these sensors, but where are the disadvantages and the gaps?

There are still communications Gaps, it is a technical problem to come up with easy solutions for every environment, so from a jungle to a volcano to an ocean, you have a few specialists around the world, and so new solutions need to keep evolving. If you try to do a big science project, there are problems with reliability and reproducibility, being able to maintain it and carry it after the project finishes. Also, costing is sometimes hidden, it may be cheap to build the sensor itself but then might be super expensive to build a secure "cage" for it, that aligns with the environmental conditions. Some people from India asked help to monitor water in the Himalayas but due to the harsh conditions it was not possible even though the sensor was available.

5. Do you believe that once the sensor is fully developed, climate change and pollution will be easier to understand and tackle?

Definitely. One of the problems regarding climate change is that it's all down to the locals and scientists to report events, anything that makes that reporting faster and cheaper is helpful. It is easy for developed countries to run to places around the world and measure certain parameters, but it's not so easy for developing countries to say they need to know the pollutants in their place. The development of these sensors is for sure a contribution.

6. How long from now do you reckon we will be able to have reliable data from the sensors? Where do you think the funding should be invested?

Reliable data has been shown in reports already and is possible. What should be funded is tricky, there are probably 4 or 5 different areas that could use funding, such as prototype projects using the space networks that are cheap to use, mainly things that can communicate with satellites, this could revolutionise what we are doing (talking about a 100$ microsatellite that is embedded in a certain system, it was designed to use in remote places for agriculture, monitoring water. Those last for a while since they can be turned off most of the day). Politically we should fund all that is related to climate change and pollution, water monitoring research, mass migrations, mass landslides, everything that pictures danger.

Professor Theo Damoulas – University of Warwick

1. Please introduce your research. What are the aims?

Machine learning research based on statistics, more specifically I am studying problems that have an additional structure that needs to be incorporated in designing methodology and algorithms, inductive bias in machine learning. We can think of it as anything from a simple structured prior knowledge a human has about a problem to dependency structure, so spatiotemporal problems, or problems and processes unfold over structure domains such as road networks in cities, or environmental ones where there are a lot of constraints. Regarding air pollution project we have very complex spatiotemporal dependencies, forecasting as input, in order to estimate and predict pollution first we have to integrate multiple sources of information that might be very different in terms of sampling resolutions, we might have ground sensors measuring air pollutants, some other ground sensors measuring other pollutants, at that level you want to borrow statistical strength between those cause they have common imitation sources, meaning that we might want to jointly model all or some of the pollutants into one sensor, so we if we learn the internal dependency a much better job could be done in the areas with gaps. We might have different sensor networks that are sampling very different periods of time, one measured every minute, another every hour. Also in space we can be considering ground sensors or remote sensing satellites and numerical models based on their data.

Another important aspect is that this is a physical process and up to a level we have physical conservation laws that need to be respected, so as we learn a model of statistical machine learning, these models don’t necessarily respect conservation laws because they are correlation based, they learn correlations to predict something. Of course it is a physical process if we estimate an air pollutant in a spatiotemporal box somewhere in the city and let’s say it has been done a really good job and we have concentrations of the air pollutant estimated there, given a specific wind profile and the topography of the city, that should provide a lot of information about what will happen in the next box in space in the next time interval assuming it is in the same direction of the wind, let’s say. Another component that comes in are the physical conservation laws, some very structured prior knowledge we put in the form of a dynamical system. A second component of interest for policy makers is “well ok, they like the estimates, they like the forecast, and they can have the weather forecast on TV which is important for the public" but what public and policy makers use to create policies and make decisions are the What if? Scenarios. Scientifically, these 'what if scenarios' require causal knowledge and not correlation knowledge, so it's not enough. In what if scenarios we are doing counterfactual reasoning, 'I am observing a process, but I want to imagine how that process would have been if I did that' and that is the definition of counterfactual reasoning, we need to know the causal and deeper relationship between variables, applying to this scenario we need to understand the deeper relationship between car emissions, different car types etc. Another thing we are actively researching is this data driven causal discover, causal discover is when you try without knowing the exact degree of the causal relation between 2 variables, but you know that one causes the other, you know the order, the direction of the arrow. Two main frameworks, one is from statistics called the potential outcomes, another framework is coming from structural causal model's graph based where graphs depict the directionality of which thing causes what. If we consider air pollution in one specific area, traffic causes air pollutants, emissions from industry or houses too, and the wind is a dispersal mechanism, so if we consider air pollution in one specific area, we can say that its caused by emissions in one area and then transported by the wind to another area. And then we go through the What if scenarios using sequential decision making with causal information, so I want to optimise and find from a set of actions that I have in my disposal, the optimal decision in space and time such that I maximise or minimise some expected values like the expected level of air pollution in determined area.

2. What would you say it's the main issue in the environmental air quality? What makes your technology so important?

There is definitely a component of education for the public about the limitations and assumptions and advantages and benefits of AI technology. We need to understand that data is not information, data contains information. People put local sensors in their houses and look at raw data and they observe things like a huge spike without understanding various things including that it might be a problem with the sensor, noise, quality of sensor deteriorates in time, requires calibrations, it is affected by humidity, temperature, various other factors. So, this is what AI, statistics, mathematical modelling comes into play and It kind of says that: there is a signal and there is noise, and we want the signal, so we need to model the data effectively to get access to the signal. Local sensors and sensing in general need models to be able to integrate and capture different signal to noise ratios of the quality of the sensor, also need certification of sensors with specification that measurements may not correspond to reality because we do not have a ground truth. Unless we have a perfectly calibrated laboratory level experiment in a controlled volume of the atmosphere, where you can measure exactly, then that would be your ground truth, but that's not what we have. We have reference grade sensors, roughly 100x in London those get manually calibrated, they are very high quality but still need to be calibrated once in a while in fact even after the calibration the data produced by it is recalibrated based on mathematical descriptions and that is what we have close to the ground truth. From there to local sensors there is a huge gap, of course there is a range of sensor devices and I think it is important for public to understand or appreciate all of this dimensions and that's why even if we have super accurate sensors, we would need to place them everywhere, and that is not possible, we will need an infinite number of sensors to produce a continuous index or concentration measure of air pollution.

3. How does your development differ from other types of technologies?

Air pollution is a big problem with historical approaches, attempts to measure it, to model it, to act on it. I guess focusing in recent years, the state of the art in terms of modelling air pollution has been focusing on mechanistic models, we can think of it as a mathematical description of the dispersion diffusion process across buildings and across the physical world. These techniques rely a lot in structural physics information, which is fantastic, but now we live in an era that we do have a lot of data, not only for the pollution but for the drivers of pollutions as well, and this models are not very straight forward to assimilate data, there are also very expensive to run at high resolution, you need to rely on the geometry of every building, deal with complex factors like turbulent flow one of the grand challenges. We are taken from a data driven perspective, the golden intersection is not one methodology against the other but more like a blend of both, embedding constraints and conservation laws and physics inside power data driven probabilistic models. We integrate remote sensing, ground sensors, information about the environment, the street network, some models can even provide information with traffic cameras that counts the number of vehicles passing and detect vehicle type, and based on that we get information about emission levels. Going towards the What if scenarios, allow us to move towards this.

I will summarise by saying that our approach differs because it is scalable, transferable to other cities, is data driven and incorporates prior knowledge, physics, causal relationships that can exist in the real world, and it complements the spectrum of approaches that are out there.

4. Where do you think are the gaps in the sensor research and development?

When we think of environmental problems in general, a lot of what the final goal is and the final output of it, is usually decision making. We are monitoring an environmental process to act on it, in order to improve it. So in a way, if we think of it as two separate components, one is estimating, modelling and forecasting interpretation and understanding relationships etc and the other one is decision making on it, then the biggest gaps exist in the second part, the what if scenarios, intelligent decision making, human machine interplay in the decision making. In terms of its science, how exactly do we do that? I would Argue that there are less scientific technical gaps in the first component because we do have a range of very powerful modelling techniques, from statistics, AI, machine learning, mathematical modelling for estimating and forecasting. There are still questions, I am not saying that it's completely solid, processes are changing and evolving. There are challenges in being able to track those dynamics that are driven by external factors still in the first component. Regarding the second component, scientifically is very challenging, other challenges have an interplay of science, policy and public so communication of science, understanding of science, limitations, assumptions, better practices on how to use technology, there are challenges in data privacy, security, challenges in scaling up and making it accessible and open.

5. How long from now do you reckon we will be able to have reliable data from the sensors? Where do you think the funding should be invested?

Tough question, we've done research on this on a fundamental level and applied level, development of techniques, advances the state of the art developed a cloud-based system. At some point it's no longer an academic exercise, at that level someone must step in and do the next step. If we think of the ladder of research needed to develop a product, it is a big ladder. From applied research to really having a product it's a long way. Obviously, everything needs to be funded, fund basic research, fund applied research, cofound with the industry to do the next step, at the same time we need to fund policy makers and local authorities to be able to have the capacity to use technology, train the personnel, develop systems able to use the technology.

Dr Firat Guder – Imperial College London

1. Please introduce your research and what are the main aims of it?

Me and my team's research aims to build intelligent interfaces that connect biology with machine or chemical systems with machines. The kind of research that we do is we build mainly sensors. Then we invent the materials and obviously we functionalized these materials to send specific targets - chemical or biological targets. Then we build the hardware. The electronics and software is around this to really extract information from biological and chemical systems. So that's kind of what we do. And then we obviously use machine learning and etc. and other software approaches.

2. What do you think is the importance of low cost environmental monitoring sensors and how does it differ from other types of technology?

I think when you do things at low cost, that means that you can do more often which is just really powerful and it's if you have lots of data then it can take this data and turn it into insights. So this is really the main. I would say that in my in my view is the is the main advantage of low cost sensors just they are able to create high volumes of data at higher frequencies allowing to provide a different dimension of insights into what's happening. Then you would capture for example air quality monitoring. If you have one or two stations in a city, clearly there is a lot of gaps in terms of spatiotemporal resolution. So you need to make a lot of guesstimates but if you have low cost sensors even if the performance are not as good as these expensive measurement stations or labs measurements you still have higher volumes of data.

3. So obviously it being low cost, but what would you say are the main advantages apart from that one regarding this type of sensors and disadvantages as well?

They can be operated at the point where you need them. So that's kind of the idea, you don't need specialized personnel making these measurements and then you don't need specific training to basically carry out these measurements. Obviously, they don't cost so much, and you just take them around with you. It's all about tradeoffs, right? So when you're gaining things, you have to give up things, you know. For example, if you don't have specialized users, then you can have obviously more user errors, it may not be as good as someone that's really trained in that area, making the measurements.

The other thing is the performance of the sensors. Oftentimes you're trading off the method there - the higher performance measurements with portability and low-cost. So if you usually go low cost your constraints are just different. With low cost system measurements you don't have access to the same obviously infrastructure. So the kinds of measurements that you can make, it's just the number is just larger.

4. Do you believe that once the sensor is developed climate change and pollution in general will be easier to understand and tackle?

Pollution, I would say definitely yeah. You know if you don't really understand it, it's really hard to action on it. And then if you wanna control it you need to make measurements all the time. Climate change I'm actually less optimistic. I don't think it will be able to even if you make more measurements.

We already know more or less how things are, what's happening. The incentives are not about the measurements there, it's about implementation. Even if you measure something, if there is no action, actually the measurement is not that important. Climate change is a big problem to solve, and it has many moving parts and different stakeholders. But pollution in general, if we look at it, you know, like air pollution and then water pollution and cetera, more measurements definitely make a difference for sure.

5. Where do you think are the current gaps in research and development for these sensors?

There are huge opportunities in terms of combining, you know, computational methods like AI and so on with low cost sensors. Uh, that's definitely under exploited. I think there's a huge opportunity there. Uh, in terms of like, if we look at biological and chemical sensors like sample prep is always a problem. You know that's a bit of an issue. In terms of getting, there are a lot of concepts out there, but you know, starting companies and so on from the lab is always so difficult. So we definitely need like seed fund more these initial ideas so that they can go out of the lab. What else? I mean, if we look at specific funding agencies, for example, like EPSRC doesn't really do food, they do medicine. So they fund medicine and technology most of the time they don't want food and technology and then BBSRC does not, fund really technology. So there is NERC I guess is similar to that. There is definitely a problem with funders. The biggest, the biggest funders in in the UK they are not really doing like food or environment. They are doing, you know, health care and technology and technologies related to that. So I think there is definitely a big funding gap in terms of, food and environment and technology because they are just underfunded for sure.

6. Where do you think funding should go to and where do you think it should be invested?

Funding should be more invested in the areas of food and environment technology. Environment is behind on funding, in my opinion. So funding needs to go in that direction for sure.
We certainly need to do fundamental research. But we do need to also invest money into like seed funding ideas. The researchers themselves, they need to be empowered. So the funding should go to the researchers. Take ideas forward basically.

7. How long from now do you recommend that we will have will be able to have reliable data from this type of sensors?

I mean, we already have reliable data from them. It's just that we don't have many different sensors that are out there that can work really well. And also if you if you look at physical sensors, I mean they're on everyone's phone, right? So they're everywhere and then they are producing reliable data. If you look at chemical sensors, it's definitely less and biological is the same way. So we just need to build more of them and come up with technologies. That's about translation and taking things out of the lab. And so if we have well supported researchers, then we'll have much shorter time taking these ideas out of the lab and they become more commercial and that's it. So how long before? It depends on how much we are willing to invest in the researchers so that the idea gets to get out.

8. Have you been or are you in touch with the policymakers?

Yeah, but could do more on that front, for sure. There's always a disconnect, I think, with the policymakers and the scientists that are in the lab. And I think it's a complicated problem. I can tell you that I would be reluctant to go and spend time with the policymakers because I'm not even sure if there will be any impact. If I put in effort into my research, I know that something will come out of it whether it gets adopted or not, that's another story. If I put a lot of effort into changing policy nothing may come out of it and that's it! All the time is wasted. If the recommendations are taken really seriously, then obviously people would be more incentivised. But perhaps there is the notion that it's not taken seriously, right? My time is better used in the lab training people and just not worry about these other things. It's just the realistic answer essentially.

Nicholas Davies - Senior Committee Specialist with the Environmental Audit Committee

1. To what extent is water pollution and air pollution of concern to UK policy makers?

To introduce myself, my name is Nicholas Davies. I'm a senior policy specialist for the environmental audit committee, a cross-party organisation. We scrutinize, all of the government public bodies for their environmental performance against environmental targets. In that role, I managed an inquiry on water pollution in rivers which was carried last year, started in March last year. We concluded and made our final report and recommendations to the government in January this year. That was very important.

The state of UK rivers has been of great concern to policymakers in the last year, especially after having probably been ignored for so long. It has risen up the agenda in the last year, only 14% of rivers in England are meeting good ecological status. And that status is set out in the in the laws that we inherited. Over the last sort of 10 years has meant that there is increasing figures and data on how many times those storm overflows releasing untreated or partially treated sewage into rivers. Because there was the environment act passing through parliament last year there's been immediate concerned and increasing media attention to water quality. Finally, because of our inquiry on the environment's loaded committee, it has put it on the on the political agenda as well.

It has been, and during the debates on the Environmental Act, it became a very hot political issue, to the extent that members of parliament were facing a lot of pressure from their constituents about sewage pollution in rivers.

2. How are government initiatives addressing these types of issues?

The environment act was passed late last year and is going to address these issues in a number of ways. It is brought in a requirement for water companies to progressively reduce the number of discharges from storm overflows. The secretary of state for DEFRA (the department for environment food and rural affairs) has to also bring forward a plan by September this year on how the government is going to help achieve this progressive reduction. The EU strategic policy direction statement has made it clear that the water regulator needs to take tougher action and it needs to prioritize long-term improvements in the network over shorter reductions or keeping bills down. And that was a balance that the regulator was not getting right in the past, was prioritizing lower water bills rather than an improved network.

So those are things that the government has to respond to the Environmental Audit Committee's report within two months, that deadline is a wrap this week and we're hoping to have the response from the government within the next week, so it should be published very soon.

3. How can new technologies such as low-cost sensors be used to address these issues?

Well, the Environment Act introduces a number of measures, introduces a requirement on water companies to approve monitoring downstream of their sewage treatment works.

I don't know in great detail how low-cost monitoring can help within that, but it seems like there's going to be a need for increased monitoring deployed by water companies, within the next few years, specifically on water quality itself. We discovered during inquiry that monitoring now is patchy, underfunded, outdated and it doesn't cover all of the pollutants currently affecting rivers.

So clearly there needs to be improvements in monitoring.

Did you do this at all with the people from the centre for ecology and hydrology? Were they involved or, or not? They submitted evidence to us.

4. If so, what types of sensors should be prioritised? I wouldn't really be able to answer that, but it seems like we need to have better sensors, recording data, overall monitor quality of water in rivers and ones that may be consider a wider range of parameters than just nitrogen and phosphorus, if possible. Also, in terms of wastewater treatment

plants, we need to understand the volume that is being discharged as well, and at the moment event duration monitors, they only record when the discharge starts, and so they don't actually capture the volume of roofs that faced so that's another area where monitoring could be approved.

5. Where do you think the gaps are in research and where should funding being invested?

There are gaps, as I mentioned already, in terms of the monitoring of the pollutants within water. So, the common monitoring is capturing phosphorous levels and nitrogen levels, and they are important water pollutants, but we heard during the inquiry that there's a chemical cocktail of pollutants in rivers including micro plastics and many persistent toxic chemicals. And some of those pollutants are not routinely or systematically monitored for. It's quite difficult I think to have more of a technological monitor that then monitors plastic, that does need to be in the field, needs to have a wider sense of chemical monitoring within rivers as well. And this is one of the reasons why monitoring is outdated, some of the technologies or techniques that are being used are outdated because they're not keeping up with the array of pollutants that are now affecting rivers.

Where do you think funding should be invested?

I'm not sure if I'm qualified to say that, but I we called for more Funding for the Environment Agency. And I think it would be down to the environment agency and other actors with technical experience to know where the funding needs to be prioritized.

6. How is the communication between science researchers and policy makers?

That's part of the process when we hold inquiries as part of the select committee, scientists and other bodies can submit written evidence to us. They come in, we hear from them in parliament, and we questioned them in an interview process. That's a way that scientists can engage with parliament. When we held this inquiry, we had evidence from a number of scientists, ecologists, an expert in data analysis, etc.

We've concluded our inquiry on water quality now, we'll be doing follow-up work on it probably, but for now, the inquiry is finished. We will be looking at other issues while keeping an eye and monitoring this topic. We are open to people contacting us in the future.

Professor Alastair Lewis- University of York & Chair of the DEFRA air quality expert group

1. Please introduce your research. What are the aims?

My main area of research is related to air pollution science which includes things like combustion emissions, ambient air quality and indoor air quality. As part of that I've worked on development of analytical methods from very large instruments to small sensors, for measurements of pollution and related constitutes. So, that's my area of expertise and in fact, I did work for NERC a few years ago, related to new technologies. And that includes work in the area of particularly low-cost sensor. So, it's mostly pollution measurements and sensors related to atmospheric pollution.

2. What is the importance of low-cost environmental sensors? What would you say are the advantages and disadvantages?

Well, there's a lot of potential because most of the atmosphere, (which is what I work with) is under sampled and so if we're looking at issues like population exposure to pollution, we have to do a lot of interpolation to try to evaluate what exposure we think people get rather than having the data by actually measuring it.

There are some big gaps in trying to link public health outcomes to actual measurements. In the UK for air quality, there were around 200 locations where air quality is measured using traditional techniques, it's not a lot of measurements for 68 million people. There's clearly an opportunity to improve the, the way in which exposure is assessed. That's probably the biggest opportunity in air pollution sites, and that includes also assessing exposure inside buildings as well, which typically need their own sensor. There's lots that can be done, the challenge is around having sufficient sensitivity and precision in the measurement for it to be worthwhile and that is, what's really undermined a lot of development. The use of sensors in air pollution, the sensor itself didn't provide measurements that were sufficiently accurate to be useful thought for research or for regulation or for policy, so they produced sort of traces that would tell you where the pollution was going up or down, but they wouldn't tell you very much about the absolute amount, and lots of air pollution and atmospheric science is based around legally defined and quality standards. The quality of measurements is hugely important because it's all set against a regulatory framework that measures things to very high precision because potentially somebody could end up in the high court arguing whether a measurement was above or below a legal standard. I think that this isn't really well known enough within research councils that most of the use of measurements ultimately in air pollution is used against legal standards.

So, the test there is incredibly demanding. You can't have any old junk sensor; you must have data that is high quality and traceable to standards. So not all subjects have that same constraint, but in pollution the requirement for data to meet the regulatory standards is because a lot of that data is then used in a legal context. So that's the big challenge is that, how do you get measurements that will stand up to scrutiny, within that sort of regulatory environment?

3. Where do you think are the gaps in research and development of these sensors?

One of the problems is that the UK and more widely, there's not very much work done on developing new sensors themselves. Regarding air pollution, we have lots of repurposing of existing sensors. Most local low-cost sensors that are used in air quality are sensors that have been around for perhaps 30 or 40 years, that were developed for a different purpose. And people have tried to use better electronics or better algorithms or machine learning to turn a sensor that was designed to often measure exhaust emissions into something that will measure ambient air. We have very little basic R&D on new sensors themselves. That's the biggest gap, no one wants to invest in developing new sensors. Generally, it's about packaging up existing ones, putting them in a different box, producing a nice web page, promising that machine learning will solve all the problems and do all the corrections that need to be done. We don't have very much work on basic low TRL development of new sensors because it isn't funded by any of the research councils. It is funded for other domains, but not for environmental science. You couldn't get a grant for developing the new sensor and, government bodies typically don't understand the time scale that it might take, from five years to develop a new sensor they want it in six months. So that's where the gap is, there's very little basic sensor development work being done

4. How are government initiatives addressing these issues?

There is a lot of interest in using low-cost sensors, within both local government and national government, but most people in the policy context, when they encounter a measurement, it's because of a legal challenge. Veritably few people in the policy world had interactions with the public or with organizations over air quality. They only have interactions when there's a problem, which means that if an air pollutant has exceeded for example, a legal standard, which means that the measurement is immediately thrown into the legal side.

There's a bit of problem around adopting these or recommending them, because most of the uses of that data would have some form of regulatory interaction. Because of the uncertainty, often in low-cost sensor measurements, it's been difficult because most of the interaction between policymaker and those low cost measures will be in the legal context, even though there's a lot of enthusiasm to have more measurements and to use local sensors for this. Nobody wants poor quality data being thrown into legal complications and legal proceedings. So that's been the barrier. It's not an unwillingness to use local sensors. I think people think it could be a transformative technology, but until the measurements can meet the standard that's needed to stand up to scrutiny in a legal context, the data is actually unhelpful. That's where the policy barrier is, when you have pollutants that are very, very closely tied to legal standard, it's a bit like the example I always give, the breathalysers that you would assess the amount of alcohol in blood, nobody has an interest in a low-cost, poor-quality breathalyser. It could give you wrong answers, so it doesn't help. It's only any good when it's really accurate. It either works and meets the legal standard or you don't use it.

5. How is the communication between science researchers and policy makers?

It is pretty good actually. There's a lot of research activity, there's a lot of interaction, particularly with DEFRA, which is the relevant government department. There's a lot going on I don't think you can really fault either side. There's a lot of interaction there has been funding and so on, but I think the reality is that we're often working with rather poor-quality tools that have not really been designed to reach the right sort of data standards. But I think the communication is very good, and I think that the understanding of what the end user needs is very good. I think that the challenge has been allowing the research community to try new things would be quite constraint.

6. What type of low-cost sensors should be prioritised?

I don't want to give you a precise answer to that. I think sensors can be a little bit misleading because of course the sensor implies a passive device with no moving parts. I think the biggest opportunity is probably around miniaturized devices, which could well have moving parts.

They may have pumps; they may have optical systems and so on in them. I think it's around miniaturization of some of the analytical technologies that we've got, rather than the layman's interpretation of a sensor, which is a small, passive little semiconductor that sits on a smaller electronic component that does the sensing.

Actually, I think what we need a more sophisticated miniaturized devices, whether that's miniaturized and optical systems, miniaturized mass spectrometers, etc. Right across the spectrum of analytical techniques, we haven't made very much progress at producing small compact versions of those and they're often much better at producing high quality measurements because they have a much better infrastructure for calibration and framework, and they're often compound or chemical specific, whereas sensors are often rather generic and nonspecific. So, that's what I think, how are we going to renaturise mass specs or gas chromatographs, or absorption instruments or laser induced fluorescence instruments down to the size and shape that makes them more like a sensor.

7. Where should funding be invested?

I think that there's lots of funding developed around commercialization and around bringing products to market. There's lots of funding for that, but I'd say that the gap is around actually developing basic technologies that will allow us to make measurements in new ways. Most of the, the toolkit of sensors for atmospheric measurements are from the 1980s. They're mostly sensors in one form or another that have been around for decades, we haven't really invested in new techniques. And particularly there is a lack of investment around miniaturization of well-proven measurement methods, using miniaturization topics like microfluidics and micro-optical system, there's very little R&D in trying to develop. At the moment we just keep repackaging and reworking the same old sensors over and over again. Rather than making any breakthroughs in basic analytical science that would then allow us in 5 to 10 years' time to end up with commercialisable products that would perform significantly better than the sensors that we've got today. People interpret that if it's a low-cost sensor, it must be quick to do, they start to conflate lots of things together. So, if it's low cost, it must be cheap, which means it must be quick to develop. That is a problem, there is a poor understanding of the technology landscape in any RC. It is hard to explain that low cost does not mean quick to develop. It may take years to develop a really high precision, genuinely low-cost sensor. The first sensor will not be low cost, micro processes are only low cost because we make billions after. The very first sensor that you might make could be hugely expensive to produce. This is an education problem that needs the funding. If you want new things, they will be very expensive to start with there's a problem about not understanding the roadmap, it might be quite long. If you don't fund any of the early stages of the roadmap, then you'll never get anything new at the end.

Prof. T Renganathan from IIT, Madras

1. The specific aims of your research.

The overall objective of the research is to develop novel sensors to detect and monitor AMR triggering pollutants to improve understanding of how these pollutants impact AMR. The specific objectives of the project are as follows:

I. To identify the most abundant pollutants that are reported to trigger AMR
II. To identify novel polymers for pollutant pre-concentration
III. To develop rapid, low-cost electrochemical sensors for detection of AMR genes and pollutants

IV. To develop paper based colorimetric sensors for AMR triggering pollutant
V. To study the interactions between AMR genes and co-selector pollutants

2. What do you think is the importance of low-cost environmental monitoring sensors? How does it differ from other technologies?

The conventional technology for environmental monitoring depends on sophisticated instruments, expensive chemicals, and complex procedures. All these, challenge the routine environmental monitoring of AMR triggering pollutants in both developed and resource constrained regions. The low-cost environmental monitoring sensors offer a feasible solution to overcome these challenges and enable periodic monitoring of pollutants. ASSURED criteria (Affordable, Sensitive, Specific, User-friendly, Rapid, and robust, Equipment-free and Deliverable to end-users) was set by the World Health Organization (WHO) as a benchmark for point of care application. The proposed colorimetric paper-based microfluidics sensor (LP-μPADs) and adsorptive colorimetry sensor has potential to meet the ASSURED criteria set.

3. What would you say are the main advantages regarding these sensors? and disadvantages?

These sensors are simple, low-cost, highly sensitive, rapid and does not require sophisticated instrument or trained personnel to operate. The main challenges that need to be addressed in the proposed sensing method are as follows; a. colorimetric sensor require colorless samples which may require a pre-treatment step, b. detection of some antimicrobials have interference with common ions.

4. Do you believe that once the sensor is fully developed, climate change and pollution will be easier to understand and tackle?

Yes. The low-cost sensors are the key to understand the fate and transport of pollutants. This helps to evaluate pollution control strategies and frame policies to tackle several global health and environmental issues such as antimicrobial resistance (AMR).

5. Where do you think are the gaps in the sensor research and development?

Proof-of-concept for the present sensing methodology is established in the laboratory conditions. Preliminary studies on the validation of the protocol are done by comparing with standard analytical techniques. The developed sensing method must be translated to obtain a working prototype. Integration of the developed sensing method with silicon-based photodetector must be done to build a low-cost, onsite device for detection of the selected antimicrobials and genes. The integrated sensors must be statistically validated to assure the robustness of the device.

6. How long from now do you reckon we will be able to have reliable data from the sensors?

The design and development of integrated prototype will take approximately 2 years. The statistical validation of the developed prototype will require 1 year. It takes three years to develop the reliable sensor.

7. Where do you think the funding should be invested?

The funding can be invested in developing integrated sensor and check statistical validity of the developed sensor by performing mass surveillance of antimicrobials in water bodies.

Prof. Praveen C Ramamurthy, Indian Institute of Science

1. The specific aims of your research.

We design and develop novel molecular architectures and fabricate a solid-state sensing device for specifically detecting a variety of analytes like VOC, nitrates, heavy metals like lead, mercury, and chromium ions as well as iron, fluoride, arsenic ions, and biological organisms such as E. Coli. The most important and critical aspect of the research is the decoding and elucidating the interaction that happens between sensing molecule and analytes.

2. What do you think is the importance of low-cost environmental monitoring sensors? How does it differ from other technologies?

Conventionally many of these pollutants are detected by spectroscopic techniques, however with development of these hand-held solid state sensors, detection is very simple by way of measuring change in electronic. These sensors can be better integrated at the point of use like wearable electronics.

3. What would you say are the main advantages regarding these sensors and disadvantages?

Since the device is a solid-state sensor, all computing, data management and display can be integrated through the smartphone, thereby reducing the cost and complexity of the sensor. Calibration is another advantage in these types of solid-state sensor compared to spectroscopic and electrochemical sensors.

One of the disadvantages, is temperature drift; however, electronics can be configured to have temperature compensation to an extent.

4. Do you believe that once the sensor is fully developed, climate change and pollution will be easier to understand and tackle?

Based on the size and user-friendly nature of the system coupled with a smartphone, data management, mapping, real-time data analysis and historic data management will be possible to understand the dynamics of these pollutants. Complex multiparameter relationship can be visualized in a better context by having repository of these sensor data. All these will be useful in understanding and consequently tackle climate change and pollution more robustly.

5. Where do you think are the gaps in the sensor research and development?

In India, at both industry and academics, majority of the sensor R&D happens at the system integration level rather than sensor material development. More industry - academic collaboration could happen for development of materials, architecture, fabrication, packaging, data analysis.

6. How long from now do you reckon we will be able to have reliable data from the sensors?

Many faculties in various academic organisations have incubated start-ups. Hence already reliable data is available, for example in our lab more than 10 years data of some of hundreds of these sensors are available. More such initiatives are required to expand the repertoire of sensors.

7. Where do you think the funding should be invested?

I believe lot of science and technology developed at academic and research institutes are lost because of lack of opportunity for taking it further to make a usable product out of it. Funding is required for the technology start-ups and academic institutions, to help make these materials and systems in addition to create a platform for industry academic interaction. Industries should be encouraged to interact with these start-ups by the way of incentives for both. The financially supported start-ups should be evaluated based on the deliverables at the end of period and based on performance further support should be provided. This is very much required as creating a self-reliance ambiance will take some time and confidence will develop in the Indian sensor community.

Prof Sachchida Nand Tripathi from IIT Kanpur

1. The specific aims of your research.

We develop Sensor based air quality measurement networks that are comparatively easier to use, gather more data and cheaper to deploy in multiple locations requiring much smaller in structure.

2. What do you think is the importance of low-cost environmental monitoring sensors? How does it differ from other technologies?

The sensor-based air quality monitoring units can monitor a variety of parameters including particulate matter (2.5 – 10.0), concentration of gases including NO_X, CO, ozone, etc. The deployment cost is around ₹ 2-3 Lakhs, with almost 60 % cost reduction. In comparison, the integrated air quality monitoring systems, are more expensive, costing around ₹1.5 crores, requiring an air-conditioned space of about 120 sft with continuous power.

3. What would you say are the main advantages regarding these sensors and disadvantages?

The most important advantage of sensor-based systems is the wider deployability in large volumes. More the measurements, better it will be to understand the effect of the pollutants, easier to model and mitigate the effects. Not to measure is not to Manage. Many issues connected with climate change including CO_2 emission from industries/automobiles can be better managed with more measurements using sensors. Further, fusion of data collected on pollutants, with data from ambient sensors such as temperature and humidity sensors will help in more efficient thermal management in buildings leading to lower power consumption and energy utilization. In addition, sensor systems can be made smarter with the advent of IOT, Cyber Physical Systems, Large data analytics and Machine learning. The sensor-based system have a small form-factor, Wi-Fi/4G enabled, solar powered and only requiring a small area. They generate about 15 times more data with much higher speeds.

The main issues/disadvantages in sensor-based air quality monitoring units are comparatively less accuracy, precision and stability.

4. Do you believe that once the sensor is fully developed, climate change and pollution will be easier to understand and tackle?

Yes, we believe so. PM sensors have been deployed with reliable data collection at 40 different locations in Jaipur, with R-squared better than 0.75 and error less than 10 %. Extensive field evaluations have been made for more than 7 months. In addition, sensors have been deployed in 15 locations across the country, with reliable data collection, with R-squared better than 0.85 and error less than 15 %.

5. *Where do you think are the gaps in the sensor research and development?*

While there is a very high-level technology maturity and a very good eco system for sensor deployment, integration, IOT, data analytics, AI& ML, etc., there is a large gap in sensor manufacturing in the country. While a wide variety of sensors with good efficacy are being fabricated and their performance proven in labs, there is very little effort in large scale sensor manufacture in the industrial level. For example, there is no commercial sensor, indigenously manufactured for PM. The sensor market which is about 200 Million $ presently is expected to grow to about 1 billion $ very soon. Indigenous manufacture of different sensors is to be undertaken with utmost priority, to reduce the dependence of sensors from other countries, especially to tackle the problem of non-availability of sensors. In addition, good calibration facilities are required for different environmental sensors.

6. How long from now do you reckon we will be able to have reliable data from the sensors?

Very soon. Extensive field evaluations have been made for more than 7 months. In addition, sensors have been deployed in 15 locations across the country, with reliable data collection, with R-squared better than 0.85 and error less than 15 %.

7. Where do you think the funding should be invested?

The funding is required for indigenous manufacture of different sensors to be undertaken with utmost priority, to reduce the dependence of sensors from other countries, mainly to tackle the problem of non-availability of sensors. In addition, good calibration facilities are required for different environmental sensors.

Prof. Bharadwaj Amrutur, IISc, Bangalore

1. The specific aims of your research.

We wanted to develop low-cost gas sensors for environmental monitoring. Our aim was to create a smart fusion of a large number of low-cost sensors and couple them with a few high-quality and high-cost sensors, and develop data fusion techniques to achieve an affordable cost and acceptable quality for sensing for public respiratory-health related use case

2. What do you think is the importance of low-cost environmental monitoring sensors? How does it differ from other technologies?

This is unaffordable at the current prices for such sensors. Hence a low-cost sensing technology is essential

3. What would you say are the main advantages regarding these sensors and disadvantages?

The main advantage for low-cost sensing technology will be the opportunity to offer personalized respiratory health monitoring and care for every individual, especially those who are more vulnerable to respiratory ailments.

The main disadvantage will be the lack of quality data from such low-cost sensors

4. **Do you believe that once the sensor is fully developed, climate change and pollution will be easier to understand and tackle?**

Yes - we believe so - since if we cannot measure, we cannot manage

5. **Where do you think are the gaps in the sensor research and development?**

A critical problem with low-cost sensors is the interference from other analytes as well as their dependance on temperature and humidity. Without a proper study and design to mitigate these interferences, it will be difficult to get useful data at scale. This requires some additional fundamental research on the physical-chemical and material properties and their interactions. It will also require adequate characterization infrastructure to allow collecting data for analysis and development.

6. **How long from now do you reckon we will be able to have reliable data from the sensors?**

If adequate funding can be provided, we believe that 3 years is a good time to create a TRL-7 level technology.

7. **Where do you think the funding should be invested?**

The funding should be invested in

I. Creating a high-quality characterization infrastructure, which is critical to get ground truth data as well as emulate various real-world scenarios for interferences.
II. Fundamental research and development for multiple physical/ chemical/ optical/ electrochemical and other transduction approaches.

ANNEX II – WATER

Indigenous R&D in chemical water quality sensors in India

Arsenic

Arsenic (As) is a heavy metal ion water contaminant known for its hazardous nature, widely known as a carcinogenic agent. It occurs in various oxidation states and originates either from manmade sources or natural sources. Long-term consumption or exposure of As-contaminated water can cause various health issues, including severe damage to kidneys, liver, cardiovascular, renal system, lungs, bladder, and changes in skin pigmentation which can lead to various types of cancer-related to skin. Therefore, detecting and quantifying these heavy metal ions in water bodies is highly important. WHO has set the permissible concentration in drinking water as not over 10 ppb (Mandal, 2002, Hung, 2004).

The lauryl sulphate (LS) AuNPs as a localized surface plasmon resonance (LSPR) based chemical sensor for the colourimetric detection of As in water samples was reported in the literature. The method was based on the colour change of AuNPs from pink to blue with the addition of As to NPs that caused the shift in the LSPR band due to the inter-particle coupling effect. The calibration curve was linear over 5–500 µg/l As with LOD of 2 µg/l and correlation estimation (r^2) of 0.994. The optimised method was successfully applied to determine As in contaminated water samples. The concentration of arsenic found in water samples of central India was in the range 15–350 µg/l, which was found higher than the WHO tolerance limit value of 10 µg/l (TLV) (Shrivas, 2015). A colourimetric method with novel green receptor viz. glucose in AuNPs platform is demonstrated with an average size of ~44 nm and plasmon peak at ~520 nm; this glucose functionalised AuNPs showed excellent selectivity towards As^{3+} with a rapid colour change from red to bluish. The detection unit is found to possess linearity in the range of 1–14 ppb with a remarkable LOD of 0.53 ppb (Boruah, 2019). The phage display technique was used to screen As^{3+}-binding peptide. By negative screening against some representative metal cations and positive screening against target As^{3+}, phages that bind to foreign metal cations were eliminated, while those bearing As^{3+} -binding peptides were kept and enriched. After DNA sequencing and phage ELISA analysis, 5 sets of As^{3+} -binding peptides were identified, with high content of N-containing functional groups as their predominant feature. This peptide with a cysteine added at the C-terminal induces the aggregation of AuNPs, whereas the competitive binding of As^{3+} to the peptide prevents the aggregation of AuNPs. Based on this observation, a simple and sensitive colourimetric sensing assay was reported, with a LOD of 54 nM (4 µg/l) for As^{3+}. The As^{3+} sensor showed high selectivity over other metal ions, including As^{5+}, and was validated by As^{3+} analysis in certified reference material and environmental water samples (Yang, 2018b). AuNPs / sodium borohydride

(NaBH4) and tracer dye RhB based redox reaction was reported with a detection limit of 0.64 ppb and high selectivity among other interfering ions. Samples from daily life are analysed using this method (Xu, 2018). The development of polymer hydrogel-based colourimetric strip for detecting As^{5+} ions using the reduction reaction between ammonium molybdate and arsenate ions where L-ascorbic acid functions as the reducing agent were reported. The colourimetric response occurred due to the formation of blue arseno-molybdate complex and can be visibly detected down to 10 ppb. After 120 days of storage, it retained 95 % of its initial detection ability and cost approximately \$0.04 (Das, 2016).

Fluorescence-based sensing generally employs a fluorophore molecule that is changed by interaction with an analyte; there is a change in fluorescence intensity, lifetime, and anisotropy related to the energy or charge transfer process (Sauer, 2003). FRET-based energy transfer ratiometric sensor between acriflavine and RhB has been reported to detect As^{5+} with the LOD of 10 ppb. The applicability of the sensing system was tested using natural lake water (Saha, 2017). Biosensor strain, engaging genetically enhanced green fluorescent proteins (EGFP), was able to induce EGFP in the presence of As^{3+} ion. The developed device includes a compact embedded system to measure the signal fluorescence using the light sensor, programmable controllers and liquid crystal display to show the corresponding concentration of the As in ppb. The experimental results show that the system can detect and display over a range from 5 to 100 ppb (Gudlavalleti, 2017). Another class of luminescent material, Ce(III) - based coordination polymer NPs (Ce-CPN), were reported to detect As^{3+} ions down to 0.7 ppb. It was concluded that the uncoordinated carboxyl groups and para-methylthio groups of Ce-CPNs reacted with As^{3+} ions through As-S and As-O linkage leading to linear fluorescence quenching with increasing As^{3+} ion concentration (Yang, 2018a). The fluorescence of the N/Ce co-doped carbon dots is used to detect As^{3+}. In addition of As^{3+} ions, the aptamer restores CDN/Ce's partially quenched blue fluorescence of CDN/Ce because of electrostatic, leading to exponentially enhanced fluorescent signals with increasing As^{3+} ion concentration. This dual-mode assay works in the 0.5–5.8 μg/l As^{3+} concentration range and has a 0.2 μg/l detection limit (Zhang, 2019e). Eu: Y_2O_3 nano phosphor (EYN) and EYN dispersed polyvinyl alcohol (PVA) fluorescent film (EYF), with subsequent studies of sensing behaviour for the detection of heavy metal ions, particularly arsenic ions ($As^{3+)}$ in real water samples with a LOD 57.5 ng/l (=0.057 ppb) for 0–100 μg/l linear range was observed. The sensing probe Figure 10 has been examined with different river water samples and shows recovery per cent in between 98 and 105 & maximum % RSD value of 5.76 with n = 5 tests (Dwivedi, 2022).

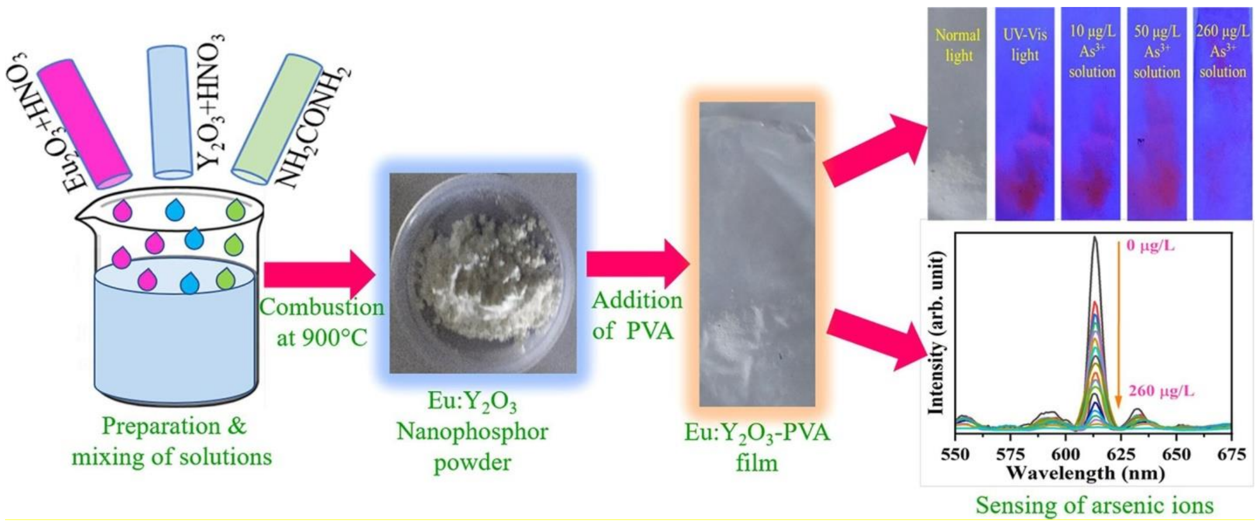


Figure 10. Graphical abstract of Eu: Y2O3 nano phosphor (EYN) and EYN dispersed polyvinyl alcohol (PVA) fluorescent film (EYF), with subsequent studies of sensing behaviour for the detection of heavy metal ions, particularly arsenic ions (As3+), in real water samples (Dwivedi, 2022).

An Au-coated, boron-doped, diamond thin-film electrode was utilised as a sensitive, reproducible, and stable response for total inorganic arsenic As3+ and As5+ using differential pulse anodic stripping voltammetry (DPASV). LODs were 0.005 ppb (S/N = 3) for As3+ and 0.08 ppb (S/N = 3) for As5+ in standard solutions. An As3+ concentration of 0.6 ppb was found in local river water (Song, 2007). GCE modified with Ag-Au alloy NPs and loaded with an aptamer was used as a biosensor for As3+ detection, which yields a LOD of 0.003 × 10−3µg/l and 0.01µg/L to 10 µg/l as its dynamic range. The operation of the biosensor is reproducible, stable, and selective, and the biosensor performs well in determining As3+ in water from natural watercourses, lakes, and wells (Yadav R, 2020). The As-specific aptamer (ArsSApt) self-assembled on a Au substrate was reported for the selective detection of As3+ with a linear dynamic range of 0.05–10 ppm and minimum detectable concentrations of 0.8 Mm (Vega-Figueroa, 2018). (E)-N'-(2-Nitrobenzylidene)-benzenesulfonohydrazide (NBBSH) was assembled on the GCE wherein three molecules of NBBSH form a complex with As3+ ions via donation of two electrons from each compound. This NBBSH/Nafion modified GCE shows the best response at pH 7, demonstrating an excellent LOD of 50 pM (Rahman, 2019). The micro/ nanoelectrode ensembles offer many advantages over macro electrodes; An attempt to explore the same was reported using self-assemblies of 3-(Mercaptopropyl) trimethoxy silane (MPTS) on the poly-Au electrode, which exists as a 3-dimensional silicate network with an abundance of –SH groups yielding a highly sensitive As3+ detection down to 0.02 ppb (Kumar Jena, 2008). An electro-active nano-textured Au electrode (Au/GNE) assemblage demonstrated enhanced electron transfer due to its unique assembly, which facilitates better electro-oxidation of As3+ ion down to 0.08 ppb (Babar, 2019). Similarly, Au wire electrode was employed for As5+ sensing at a negative potential in acidic conditions with the reported LOD of 0.42 ppb for As3+ ions and 0.55 ppb for As5+ ions (Jedryczko, 2016).

It has been reported in the literature regarding the sensor materials, including colourimetric dyes, organic fluorophores, nanostructures (metal, carbon, semiconductor, metal oxides, etc.), and bioreceptors (aptamers, peptides, whole cells, etc.), for optical detection of As in water (Devi, 2019). A novel optical liquid crystal-based apt sensor using an As-binding aptamer as a molecular recognition element was developed to detect As. The aptasensor displayed a low detection limit of 50 nM (~3.7 ppb) towards As. The potential application of the developed sensor for As3+ detection in tap water was also demonstrated (Nguyen, 2020). Hydrous ferric oxide-magnetite-reduced graphene oxide nanocomposite has been listed for optical detection of As using SPR. The developed sensing layer is sensitive with a 0.1 ppb LOD (Al-Rekabi, 2019). The Langmuir-Blodgett assemblies of polyhedral poly(vinyl pyrrolidone) (PVP)-capped AgNPs as highly active SERS substrates was utilised for sensitive arsenite detection. The sensing platform provided a chemical fingerprint for the two species of As, realising selective and sensitive determination of arsenite down to 1 ppb (Mulvihill, 2008, Zhang, 2019a). Ibumin capped carbon-gold (C-Au) nanocomposite was used as an optical sensor to detect As3+. The LOD was more superior (low concentrations; R2 = 0.96 with sensitivity 0.004 ppb, high concentration; R2 = 0.98 with sensitivity 0.0002) when compared to other techniques (Babu, 2018). Nano-enabled platforms generated from nanostructures and nanoparticles for As3+ have been reviewed in the literature (Thakkar, 2021).

Fluoride

Fluoride is one of the most reactive anions present in nature; it can only be found as organic or inorganic fluoride, not in its elemental form. It is considered beneficial when it is found as trace quantitates in water. On the other hand, excess fluoride can cause skeletal or dental fluorosis. The Limit of Fluoride in drinking water has been fixed to 1ppm by WHO. The succeeding paragraphs are some of the recent studies of detecting fluoride in drinking water.

A simple colourimetric sensor using 4-mercaptophenylboronic (MPBA) modified gold nanoparticles for rapid detection of Fluoride anions have been reported. The fluoride anions form a strong interaction with boronic acid on the surface gold nanoparticles resulting in the aggregation of gold nanoparticles, thus inducing colour change. The LOD was reported to be 0.345 μM and the linear range 10 – 30 μM. While exposed to tap water and groundwater, it shows good potential to be a practically deployable sensor (Wu, 2019). An interesting work utilising the anti-aggregation of modified AgNPs to detect fluoride ions in water samples was reported. Catechol readily reduces the Ag ions followed by the nucleophilic attack by sulphanilic acid (SA), causing the AgNPs to aggregate; hence the colour of the solution becomes brown. The addition of fluoride ions to the solution results in the anti-aggregation of the AgNPs, causing a blue shift from brown to yellow. A linear rage was reported from 1μM to 10 μM with the LOD of 0.2 μM. The sensor was exposed to a river water sample and given satisfactory outcomes. The sensor could be deployed for field testing (Motahhari, 2021). Colourimetric detection of fluoride ions in water has been studied by utilising isatin(1H-indole-2,3-dione) as the receptor molecule. The addition of fluoride ions in the dye solutions changes from yellow to violet. The LOD reported was 0.367 ppm(Haider, 2020). Green synthesised Al_2O_3 NPs combined with $CuSO_4$ and $FeSO_4$ solution stabilised on the chitosan matrix used to detect fluoride ions. The fluoride anions bond with the hydroxyl ions on the surface and form a complex leading to the aggregation of the NPs, thus resulting in a colour change from yellow to green. The LOD was reported at 0.052 mM. The sensor also showed the ability to detect fluoride in river water samples (Yadav, 2020).

Cadmium

Cadmium naturally occurs with an oxidation state of +2 (Cd^{2+}) and is found naturally along with lead and zinc sulfide ores. Due to untreated industrial effluents, mining discharge, and agricultural wastewater, Cd leaches into water bodies. Cd accumulates inside bio-organisms due to its comparatively high biological half-life of 10 – 30 years. Cd affects cell proliferation, cell differentiation and cell apoptosis. Cd binds itself with the mitochondria and inhibits cellular respiration and oxidative phosphorylation even at low concentrations. Cd is marked as a carcinogenic element by the International Agency of Research of Cancer (IARC). Cd poisoning is the major contributor behind the Itai-Itai disease outbreak in Japan. Thus, recognising Cd^{2+} in drinking water has become essential in today's life.

Thio-glycerol (TG) capped cadmium selenide (CdSe) quantum dots (QD) with an average diameter of 2.5 to 2.8 nm were used to detect Cd^{2+} in water samples using fluorescence spectroscopy. The thiol groups present in TG were bonded covalently to the core of the CdSe QDs, leaving behind the free OH groups, which causes selective binding sites for the Cd ions. The reported range is 5.0 -22 μM, and the limit of detection (LOD) is 0.32 μM, which is well within the WHO limit (Brahim, 2015). A nanocomposite material comprising of mesoporous silica immobilised with 4-tert-octyl-4-((phenyl)diazinyl)phenol(TPDP) was developed to detect cadmium in wastewater samples using UV-Visible spectroscopic technique. The LOD of this study was about 0.33 ppb which is well inside the permissible WHO limit (Awual, 2018). An immunochromatographic strip based sensor using AuNP and monoclonal antibody anti-Cd(II)-ITCBE (3A9) was developed to detect Cd in water samples. The sensing assay was based on the competitive binding of the Cd-ITCBE antibody to the test zone to the Cd-ITCBE complex in the sample. The increase in Cd concentration results in the weakening of the bright red colour of the assay. The detection limit was recorded to be

0.2 ng/ml, which is well within the allowed limit of Cd. The ease of use and sensitivity makes this a good choice for field testing (Song, 2018).

Label-free AuNPs stabilised by glutathione (GSH) at high salt concentration has been studied to detect the concentration of Cd ions. The carboxylic (-COOH) and sulfhydryl groups present in GSH form many complexes, resulting in a decrease in free GSH in the salt solution and decay in AuNPs stability. The LOD measured using UV- Visible spectroscopy is about 5 μM, while it was used to measure Cd in both spiked and rice digestion samples (Guo, 2014). A colourimetric probe using AuNP functionalised with 4-amino-3-hydrazino-5 mercapto -1,2,4-triazole [AHMT] has been used to detect Cd. AHMT was adsorbed onto the AuNPs by ligand exchange reactions; when Cd2+ ions are added, they aggregate AuNPs by chelation reaction with AHMT. The LOD using UV-Visible spectroscopic methods is 30 nM, while the linear range is reported as 60 – 480 nM. Even though the LOD falls well within the permissible range, the linear range seems very limited, which could be an issue in field deployment (Wang, 2013). A colourimetric probe using Au-Ag NPs modified with L-cystine was used to detect Cd. The ratio of Au to Ag was taken 0.3: 0.7, and at a pH value of 6, the sensor showed its best performance. The LOD was 44 nM and range of 0.4 to 38.6 μM, with being reported of successfully tested in case spiked samples, tap water and lake water samples the sensor shows promise of practically field-deployable unit (Du, 2018). AuNPs modified with DL- mercaptosuccinic Acid (MSA) were reported to detect cadmium in water samples. MSA forms a Au-thiol bond to adsorb on the surface of the AuNP while the remaining -COOH group provides the required hydrophilic interface to react with Cd2+. The LOD of this study was noted to be 40 nM, whereas the linear range was seen from 0.07-0.20 μM. The ease of use and speed of detection shows the possibility of deployable field sensor (Chen, 2016). Another colourimetric assay uses AuNPs by using di-(1H-pyrrol-2yl)methanethione (DP) as a functionalising agent. The detection range using a UV-Visible spectrophotometer was reported from 0.5–16 μM, while the LOD being 17 nM makes the sensor a practically possible option for field deployment (Sung, 2014).

AgNPs modified with chalcone carboxylic acid (CCA) shows the visual colour change from yellow to orange and act as a colourimetric probe to indicate Cd. Sulfonic groups present in CCA form the basis of attachment with AgNPs, whereas the carboxyl and hydroxyl (-OH) groups present to interact with Cd2+ and form a stable complex resulting in aggregation of AgNPs. The LOD using UV-Visible spectroscopic technique is 0.13 μM and the linear range reported was 0.227 to 3.18 μM. Successfully tested in a spiked water sample and real water samples can field deployment (Dong, 2017). AgNPs modified with 5-sulfosalicylic acid (SSA) have been studied as a colourimetric probe for Cd. The sulfonic groups present in the SSA causes the attachment to the AgNPs, and the carboxyl groups act as the interaction centre for Cd2+ ions. Using UV-Visible spectroscope, the LOD was found to be 3 nM and with a rapid response time of 2 mins and a good recovery rate of 99%, making this sensor an excellent candidate. It was reported to detect Cd in many different real samples like tap water, milk, urine, lake water, serum, etc. and makes it a good option for practical usage (Jin, 2015). For facile and sensitive detection of Cd2+, a colourimetric probe using AgNPs functionalised with 1- amino-2naphthol -4- sulfonic acid (ANS) has been developed. The presence of Cd2+ causes a visual change in colour from yellow to red due to cooperative metal-ligand interaction. The linear range of the reported sensor was 1.0 -10μM and a LOD of 87nM and possible candidate for a practical and field-deployable sensor with satisfactory results obtained from different real samples like lake water, serum, and milk powder (Huang, 2016).

AuNPs functionalised with cysteamine and cross-linked with DL-glyceraldehyde(DL-G-CA-Au) was reported as an effective sensor for determining Cd2+ ions in different water samples. The mercapto group present in cysteamine cause the interaction with AuNPs and forms S-Au bonds; the amine groups of CA cross-link with DL-glyceraldehyde, thus creating freely available –OH groups that act as a donor site for binding Cd2+ ions. A visual colour change of red to blue could be seen at an optimal pH of 7.0. The sensor has a reported LOD of 21 nM, whereas the linear range is from 0.05 to 500 μM. It has also been used to test real water samples from tap waters, industry effluents, river water etc., making it one excellent candidate for field deployment (Yadav, 2018). AuNPs modified with chitosan dithiocarbamate (CSDTC) was used to detect Cd2+ ions in real water samples. The amine group (-NH2) forms the CSDTC, whereas the –OH forms a coordination site for Cd2+ ions. The UV-Visible spectroscopic probe showed a LOD of 63 nM, whereas the linear range was 50-500 μM. The sensor was exposed to various water samples ranging from drinking water, tap water, river water, canal and industrial effluents and reported satisfactory response. This sensor has the promise of being one that could be deployed in the field (Mehta, 2015). Phytosynthesization of AuNPs using the aqueous leaf extract of rosa indica – Wichuraiana hybrid showed great affinity towards Cd2+ ions after being functionalised by glutathione. Phytosynthesis or green synthesis basically refers to reduction of chloroauric acid in presence some green reagent instead of chemical ones resulting in less production of unwanted chemical by products. The detection limit recorded was 30 nM and also showed the potential to be used in different water samples (Manjumeena, 2015).

Sensitive and rapid detection of Cd2+ ions using AuNPs functionalised with 2,6-dimarcaptopurine has been studied. The mercapto groups form an Au-thiol bond, whereas the amine groups provide the required binding site for Cd2+ ions. The UV-Visible spectroscopic study shows a LOD of 32.7 nM, whereas a good linear range from 0.75 to 3.0 μM has been observed. The sensor has been tested in various samples such as milk, honey, lake water, urine and shows good promise of being a deployable field one (Hu, 2017). Guanidine thiocyanate (GT) coated AuNPs have been reported to sense cadmium in environmental samples. Here in this study, GT is used to control the size of the particles. Also, it forms a stable complex with Cd2+ helping detect Cd. The linear range reported is 25 nM to 50 μM, and LOD reported 10 nM. While using different samples like water and food samples shows excellent response, making it feasible for field deployment (Bhamore, 2021). A metal-organic framework (MOF) utilising manganese (Mn) have been reported to sense Cd^{2+} ions in water samples. 3,3'-(pyridine-2,5-diyl) dibenzoic acid and $MnCl_2 \cdot 4H_2O$ forms the heart of the MOF. It is then drop cast on the surface of the cleaned glassy carbon electrode (GCE). The porous structure of MOF traps nitrogen atoms which shows affinity towards Cd^{2+} ions. The electron transportability of the MOF increases post binding with Cd^{2+}, resulting in a steady increase in peak current with an increase in the Cd^{2+} concentration. The LOD was calculated to be 0.12 ppb in the linear range 0-60 μM. The sensor was exposed to natural water samples and showed satisfactory results (Li, 2019).

An electrochemical sensor based on composite modified amine functionalised Zirconia MOF and carbon nanotubes for detecting Cd was developed. The amino groups present on the surface of the modified electrode present binding sites for Cd^{2+} ions. The sensor showed a good linear relationship of 0.5 ppb to 170 ppb with a LOD reported 0.2 ppb (Wang, 2021). An N-[(Benzyloxy)carbonyl]-l-alanyl-l-prolyl-l-leucine-N-cyclohexylcyclohexanamine (Cbz-APL) tripeptide modified GCE based sensor was reported for selective detection of Cd^{2+} in water samples. The present alkyl and benzyl side chains not only increases the adsorption concentration. Sites also bind Cd^{2+} to the electrode surface, increasing the peak current with an increase Cd^{2+} in a low detection limit of 4.34 fM over a reported linear range of 0.15 to 0.1 pM, making it very sensitive to even minor changes concentration (Kokab, 2020). An electrochemical sensor based on vinyl functionalised multi-walled carbon nanotubes modified platinum (Pt) electrode was studied to detect Cd^{2+} in water samples. The LOD was measured to be 0.03 μM (Aravind, 2018). Cellulose acetate (CA) modified zinc oxide (ZnO) NPs based electrochemical sensor has been reported to sense Cd. The CA modified on the ZnO surface enhances the active binding site for providing a viable platform for charge transfer for the electron hence increasing the peak current. The reported linear rage is 0.1-0.5 μM, and LOD is reported 0.41 μM (Padmalaya, 2019). Deinococcus radiodurans, a genetically engineered red pigment-producing bacterium, were studied to sense Cd in water samples. The change of colour could be observed after 24 hours of the incubation period. The detection range reported was 50 nM to 1mM (Joe, 2012).

Chromium

Chromium (Cr) is present in nature in predominantly two oxidation forms trivalent $Cr^{3+}$and hexavalent Cr^{6+}. Cr^{3+} is essential for our body and hence considered a trace element, whereas the hexavalent Cr^{6+} is considered both animals and plants due to their effect on skins, nervous and renal systems, respiratory, weakened immune system. Yellowing of paddy and paddy leaves is also a sign of Cr toxicity. The major sources of Cr are industrial wastewater from tanning and electroplating industries, electrical waste, agricultural waste, and the paint industry. The limit of Cr present in water has been bound to 100 ppb by WHO. Some of the works related detection of Cr has been listed below.

Tween -20 stabilised AuNPs have been studied as a colourimetric probe to detect Cr in the water sample. Primarily tween – 20 capped AuNPs only showed response towards Cr3+, but by adding ascorbic acid (AA) to the mix, Cr6+ could be reduced to Cr3+; hence the colour shift from red to blue is observed. The working range of this sensor reported from 0.02-2.5 µM showed good linear characteristics, with the LOD being 16 nM. The sensor has been tested in tap water, river water, and lake water and gives satisfactory results. Field deployment is a concern until it selectively detects Cr6+ (Wang, 2015). A study reported on gallic acid capped AuNPs have shown their effectiveness in detecting Cr in water samples. Cr3+ was detected using citrate and thiosulfate, which masked Cr6+. Similarly, to detect Cr6+, Cr3+ was masked using ethylenediaminetetraacetic acid disodium salt (EDTA). The LOD for the reported sensor is 0.1 µM, and the range is 1.5 µM to 0.1 µM. The sensor was reported to test different water samples like tap water, industrial effluent, lake water etc. The sample shows a potential to be deployed in the field (Dong, 2016). A study presented the utilisation of unmodified AgNPs to detect Cr6+ in water samples. Here the excess reducing agent present in the AgNP solution reduces Cr6+ to Cr3+; thus, the AgNPs interacting with Cr3+ induce a colour change. The LOD was reported to be 1 nM, where the linear range was found to be 1 nM to 1 mM. Even though the sensor response was quite good in different environmental water samples, the problem lies in differentiating Cr6+ with Cr3+ (Ravindran, 2012). A paper-based colourimetric sensor utilising silanisation -titanium dioxide modified filter paper (STCP). AuNP modified with bovine serum albumin were anchored on to STCP surface, which got leached in due to Cr6+ in the presence of Hydro Bromic Acid (HBr), resulting in colourimetric change. The LOD observed was 280 nM, whereas the range was reported from 500 nM to 50 µM. The sensor was exposed to river water samples and showed good recovery (99 %- 103 %) and satisfactory results. The sensor shows potential for field deployment (Guo, 2016). A colourimetric assay utilising polyvinylpyrrolidone (PVP) capped AgNPs investigated Cr6+ in water samples. PVP and AgNPs were mixed in the ratio of 1:3; the C = O, C-N bonds are responsible for the attachment PVP with AgNPs. A masking agent, citric acid, was used to mask the interference from Cr3+. The sensor was reported to have a LOD of 34 nM, whereas the range stated was 100 nM to 2.4 µM. The sensor was exposed to real water samples, and the recoveries ranged from 93.5 % to 104.3 %, showing the potential to be used in practical samples (He, 2019).

3,4 – dihydroxyphenylalanine(L-dopa) reduced Ag nanoflowers have been studied as the sensor for Cr using the colourimetric technique. L- dopa acts as the reducing as well as the capping agent. The detection limit was reported to be 10 ppb. The dopaquinone available on the surface of the AgNPs reduces Cr6+ to Cr5+, which forms a complex with dopachrome, resulting in aggregation of the nanoparticles. The sensor was tested on the different real-life water systems and had a recovery of 97% - 107%, which states that it could deploy in the fields (Joshi, 2016). One smartphone-based colourimetric sensor for investigating Cr in water samples uses AuNP functionalised using maleic acid. The carboxylic groups present in the maleic acid contribute to bonding sites for Cr^{6+} ions. Here, the RBG card has been created for decoding the colour, which decodes each colour by different red, green, and blue spectrum values. The image taken by the smartphone could be processed according to the RGB value by a preinstalled software known as scan-assist. The linear range observed using this technique was 0.2 ppb to 2 ppb, with the detection limit as 0.1 ppb. The nature of this sensor widens the possibility of field deployment (Mohamed, 2021).

Mercury

Mercury (Hg) is present in the environment predominantly in three forms. At room temperature, the elemental Hg (Hg0) is present as liquid silvery metal. In the case of the inorganic molecule, it is present in an oxidation state of +2 (Hg^{2+}), and in the case of biomolecules, they are present in the form of Hg^{1+}. All three forms of Hg present in nature are considered highly hazardous and toxic due to their effect on the human nervous, renal, and immune systems. Another major concern regarding Hg is its ability to bioaccumulate and enter the human food chain. WHO has limited Hg to less than 1 ppb in safe drinking water. Hg discharge in the water bodies is due to primarily volcanic eruptions, mining activities, untreated industrial slurries, improper treatment of industrial waste and agricultural waste. Several studies and works have been done to measure the quantity of Hg present in water; some will be discussed below.

An effective yet simple colourimetric assay for sensing Hg was developed utilising citrate capped AuNPs in the presence of lysin was reported. Hg^{2+} ions present in the solution replace the citrate ions and form Hg capped AuNP. The Hg forms bonding with the amino acid functional group present in lysin, resulting in agglomeration of AuNP and change in colour from red to grey. The reported LOD was 2.9 nM, much lower than the standard (10 nM). The linear range is reported from 1 nM to 1μM. This sensor shows promise of being a field deployable one (Poornima, 2016). An oligonucleotide stabilised Ag nano-cluster fluorescence probe to sense the presence of Hg in water samples was studied. The LOD of their sensor is 5 nM, which is comparable to the WHO limit (1 ppb). The dynamic range of the probe sensor is found out to be from 5 nM to 1.5 nM; also, the sensor has shown good selectivity compared to other interfering ions like Cu^{2+}, Fe^{2+}, Fe^{3+}, Mn^{2+}, Co^{2+}, Ni^{2+}, Pb^{2+}. The sensor shows promise for being field deployable (Guo, 2009). A Tyndall effect-based assay was reported to determine Hg^{2+} ions using AgNPs capped with L- tyrosine in artificial and real pond water samples. While using one 635 nM irradiation source laser pointer, a red Tyndall effect emission is seen, decreasing its intensity at the presence of Hg^{2+} ions. The LOD observed was about 0.85 nM, whereas the dynamic range varied from 5 nM to 4 μM. It showed good selectivity compared to other metal ions present in water and could be utilised for field deployment (Huang, 2021). A fluorescence sensor for Hg^{2+} based senor was developed using 4-dimethylthieno[2,3-b]thiophene-2,5-dihydrazide (DTD). The sensor film was obtained by mixing DTD, PVC and DOP in 1:10:20 ration while adding them in tetrahydrofuran (THF). The fluorescence molecule shows a fluorescence around 430 nm, while the addition of Hg^{2+} shows a secondary peak at 475 nm. The chemosensor showed a very low LOD of about 2.4 nM. In contrast, the dynamic range extends upto 100 nM under a buffered pH solution of 7.4 (Ali, 2021). A green synthesis method of AgNPs by using orange peel extracts to develop a colourimetric sensor to determine Hg^{2+} ions in water samples has been reported. The green synthesised Ag NPs showed a detection limit of 1.25 µM(0.25 ppm), whereas the dynamic range was up to several 100 µM while not interfering with other ions present in the solution (Aminu, 2021). Nanomaterial coating of cysteine conjugated naphthalene diimide (CNC) bolaamphiphile coating on the etched fiber Bragg grating (eFBG) sensor has been used for detecting Hg^{2+} with the thiol-Hg^{2+} coordination interaction between CNC and Hg^{2+} in the spiked water sample. The reported dynamic-range from 1 pM to 1 µM , LOD of 1 pM, are within the required practical range with the recovery in real water sample and portability of this sensor to be considered for field deployment(Kavitha, 2021). An aptamer-based electrochemical sensor was studied.

The sensor Carbon Ionic Liquid electrode Decorated with Pt loaded carbon nanofibre, further decorated with AuNPs to form an Au- thiol bond for the attachment of the aptamer. They showed a very low LOD in the 0.33 fM range and the dynamic range from 1 fM to 1 µM. This sensor even showed satisfactory results in the case of a real water sample using both drinking tap water and mineral water. The extreme low detection limit and wide range make this sensor very interesting (Xie, 2021).

An Ag@Ag_2S based photo - electrochemical based sensor have been reported to show a drop in photocurrent when exposed to different concentration of Hg^{2+} due to the formation of Ag- Hg amalgam, which accelerates the recombination process resulting in the drop of photocurrent. The LOD of the sensor was observed to be as low as 0.5 pM. The sensor was also used to detect Hg in real water samples like tap water, lake water, pond water etc (Zhang, 2021). A fluorescence-based sensor for Hg^{2+}using tin oxide QDs has been prepared. The sensor showed high selectivity towards Hg^{2+}. The Hg^{2+} ions get adsorbed on the surface of SnO_2 by forming Hg – O bonds, hence the large available specific surface area for Hg^{2+} is the reason for this wide linear range extending from 10^{-2}–10^{5} µM with a low detection limit of 5 nM. The sensor has been exposed to different real water samples, making it a feasible candidate for field deployment (Liu, 2021). A simple yet effective fluorescence sensor utilising rhodamine 6G dye maintained at 5.4 buffer solution for detection of Hg^{2+} ions have been reported. The sensor showed an improved LOD of 1.5 nM and addressed interference with Cu, one of the major concerns. The sensor was even tested in real water samples like river water and tap water and showed their capability to work perfectly, making field deployment a real possibility (Singh, 2021). A colourimetric sensor has been developed from electrospinning fibres derived from Rhodamine-B(RhB) or Pyrene to detect Hg in seawater samples. The fibres produced from RhB derivate are freeze-dried, and then surface modification is done using hydroxyl groups. Later on, penta-fluorophenyl methacrylate amine- (PPFMA) is used to trigger the surface grafting process and finally, adding RhBN2 makes the sensor responsive to Hg2+. The studied sensor showed a somewhat linear range from 100 nM to 1 mM(Sheeba, 2021).

Lead (Pb)

Pb is one of the most hazardous heavy metal contaminants that can accumulate in the human body through the food chain, leading to neurotoxic effects and brain diseases, such as memory decay, anaemia and mental retardation, especially in children. The WHO and the US Environmental Protection Agency (EPA) have set the maximum permissible limits of Pb^{2+} in drinking water to 48 nM and 72 nM, respectively, the maximum contamination level of Pb^{2+} in drinking water is 0.01 mg/l. Therefore, new methods for the compassionate determination of Pb^{2+} have received extensive attention in environmental and food safety monitoring. Pb^{2+} is among the heavy metal ions known for toxicity, and it ranks second in the list of toxic substances. Its presence is primarily man-made due to effluent discharge from mining and burning fossil fuels. Exposure or consumption of even low traces of Pb^{2+} is known to cause severe damage to the kidney, brain, and other organs as Pb^{2+} tends to accumulate and does not decompose.

An aptamer-based colourimetric assay was established for the Pb^{2+} detection using SiO_2 NPs as carriers of the signalling horseradish peroxidase to amplify the optical signal. The assay adopting SiO_2 NPs as an enhancer resulted in higher sensitivity with a LOD of 2.5 nM, with a dynamic range from 10 to 200 nM and 35.2 nM sensitivity was obtained compared to standard procedures. The feasibility of the aptamer-based colourimetric assay was verified by successfully detecting Pb^{2+} in water samples with recoveries in the range of 97.4–103.52 % and tested in tap water samples (Duan, 2022). Functionalised AuNPs in the presence of lignin matrixes was synthesised by the green synthesis technique of pulsed laser irradiation and the sonochemical process. NPs demonstrated a highly selective colourimetric sensing tendency toward Pb^{2+} ions within a short time interval among the various metal ions (Figure 11); the assay showed a colour change from red wine to purple, indicating the detection of Pb^{2+} ions with LOD of 1.8 μM in the linear range of 0.1–1 mM and limit of quantification (LOQ) of 6 μM (Yu, 2021).

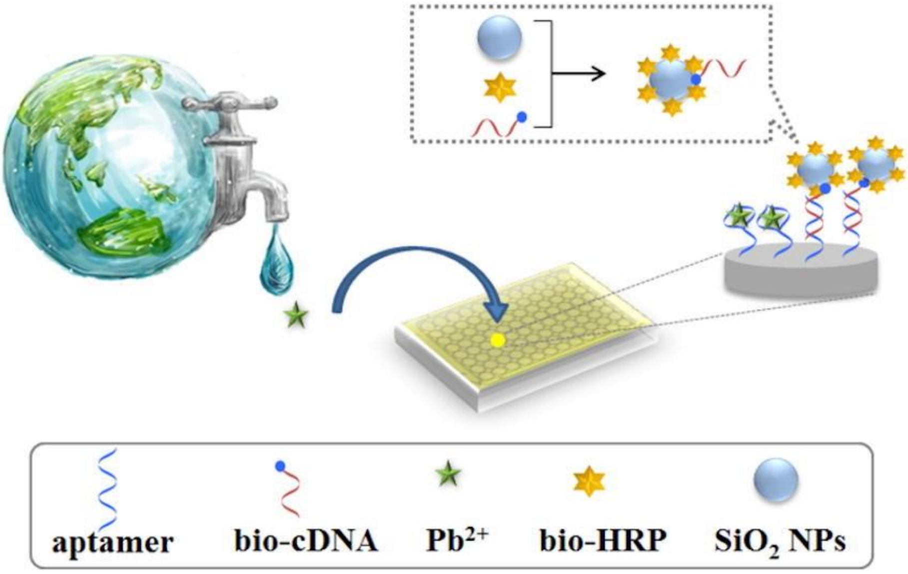


Figure 11. Graphical abstract of SiO2 NP loaded horseradish peroxidase for colourimetric detection of Pb ions in water(Duan, 2022)

Similarly, Pb in contaminated natural waters was detected using functionalised AuNPs. Colloidal AuNPs were synthesised using tannic acid as the reducing agent; this reagent allowed selective determination of Pb in 10 µl of water, with a detection limit of 310 ng/ml with an analysis time of 5 min. The coefficient of Pb^{2+} variation within the working range of the assay (520 ng/ml–13 µg/ml) varied from 1.3 % to 9.2 %. The LOD using this method with a sample volume of 50 µl was 60 ng/ml. The coefficient of variation for the Pb over the working range of the determined concentrations (80 ng/ml–25 µg/ml) varied from 0.2 % to 9.3 %, while the values for the inter-day assay (n = 8) were less than 10 %. The method was employed to analyse river, lake, marsh, and spring water; the recovery of lead was determined to be 72.5 %–130 % for 10 µl of water and 93.6 %–114.7 % for 50 µl (Berlina, 2015). Pyridine-formaldehyde functionalised AuNPs were used to detect lead in aqueous samples. The detection limit of Pb^{2+} for the AuNP sensing system was 4.0 µM with the naked eye and 1.0 µM with UV-visible absorption spectra, respectively (Lei, 2019). New triazole-acetate functionalised AuNPs (TTA–AuNPs) for sensitive and selective colourimetric detection of Pb2+. The best detection of Pb2+ was achieved in a pH range from 5 to 10 with LOD as 16.7 nM. Furthermore, TTA–AuNPs were applied to detect Pb2+ in lake water with low interference. The recovery ranged from 97.6 % to 102 %, and RSD from about 1.2% to 1.6% (Lee, 2014). Monodispersed L-glutathione stabilised AuNPs were used to detect Pb in an aqueous solution. A broad linear range from 0.1 to 30 µmol/l and a low detection limit of 0.1 µmol/l was obtained with good cross-sensitivity (Mao, 2011). Luminescent Pb clusters were synthesised into the cavities of synthetic F9-NaX zeolites, which were used as scaffolds to confine and detect Pb2+ ions in water through a fluorimetric mode. These Pb-F9 samples display an intense cyan emission in a dehydrated form. Also, a correlation between the luminescence intensity of the materials and the lead loadings was observed, with a low limit of detection of 1.248 ppb and a limit of quantification of 3.782 ppb (Moreno-Torres, 2021). Plasmonic colourimetric sensing using AgNPs and paper-based analytical devices (PAD) for selective detection of Pb. The mechanism of colour change and redshift (Δλ) of the LSPR band from 410 nm to 550 nm was reported due to the interaction of Pb2+ ions towards the PVA through strong ion-dipole interaction perturbing the stability of AgNP. The calibration curve gave good linearity in the range of 20–1000 µg/l with LOD of 8 µg/l by colourimetry and 50–1000 µg/l with LOD value of 20 µg/l using PADs. In addition, the results obtained with UV–Vis and PADs were compared with ICP-AES for the quantitative determination of Pb2+ in different water samples, including surface water and industrial wastewater samples with an RSD value of 3.4%. The concentration of Pb present in surface water and industrial wastewater samples were found in the range of 130–1055 µg/l (Shrivas, 2019).

Successful implementation and development of an electrochemical methodology for the rapid (60 s) and effective simultaneous electrochemical detection of Pb in water, with Au-screen-printed electrode probe was reported with wide quantification range of 5–300 µg/l, with detection limits below the EPA maximum contaminant levels for drinking water of 0.015 mg/l. The electrochemical sensors were tested in high temperature and humidity conditions in remote areas of the Amazon River, highly affected by mining-related heavy metal pollution. The results are expressed as the mean of three replicates with their deviations associated to the quantification with standard addition method at 95 % confidence level (Bernalte, 2020). Graphite pencil lead (GPL) covered with Au nanodendrites (AuNDs) (the AuND@GPL sensor) has been demonstrated as an electrochemical sensor for simultaneous detection of Pb2+ with a LOD below 0.2 ppb. The sensor-to-sensor reproducibility was reasonable (relative standard deviation below 4.6%). Natural lake water samples were analysed with the AuND@GPL sensor to detect Pb2+ accurately (Giao, 2019). Disposable carbon electrodes coated with Au nanostars (AuNS) were employed for the electrochemical detection of Pb. The regression model for Pb2+ exhibited good linearity with an R2 value of 0.98, with LOD of 20.55 ppb, LOQ of 62.26 ppb and linear range of 62.3–215.6 ppb. The AuNS sensor was tested and validated using a water sample obtained from groundwater monitoring wells located in two contaminated sites in Massachusetts (Dutta, 2019). The new and selective magnetic ion-imprinted polymer (Fe3O4@SiO2@IIP) was synthesised using 2-(2-aminophenyl)-1H-benzimidazole and 4-vinyl pyridine as a ligand and functional monomer novel polymer were utilised for modifying an electrochemical sensor for detection of Pb ions in natural water. The assay gave a LOD of 0.05 ng/ml over a wide linear concentration range of 0.1–80 ng/ml (Zhou, 2018b).

The effectiveness of using portable X-ray fluorescence (pXRF), with the help of waterproof film, to determine the concentration of the Pb in polluted water was assessed through indoor and field studies. The penetration depth of X-rays in water was found to be between 2 mm and 4 mm, and a water sample of at least 4 mm in depth was thus suggested. The minimum detectable concentration for Pb was 28 ppm. Based on the indoor study, the pXRF results were comparable with the certified concentrations of prepared solutions (R2>0.99 for Pb). The field pXRF readings also showed an excellent linear correlation with the corresponding laboratory results(Zhou, 2018b). A new method based on dispersive micro solid-phase extraction (DMSPE) and total-reflection X-ray fluorescence spectrometry (TXRF) is proposed for multi-elemental ultra-trace determination of heavy metal ions. Mercapto-modified graphene oxide (GO-SH) demonstrates selectivity towards Pb. The high enrichment factor of 150 allows obtaining detection limits of 0.083 ng/ml. The method is suitable for water analysis, including a high salinity sample (R. Sitko, 2015). An alternate and convenient method were reported for monitoring Pb in drinking water. This method is sensitive with a LOD value of 0.3 ng/ml. The colour on the prepared SPE disk provides an initial estimate of the degree of contamination for some transition metals with colours, such as Ni and Cu. Finally, this method involves no toxic chemicals in the analysis (Hou, 2003).

An optical fibre-based SPR sensor was reported for detecting Pb ions in an aqueous medium. During the experiment, a U-shaped probe as a sensor unit was utilised. An environment-friendly and biodegradable material, namely chitosan, is used as the sensitive material accompanied by glutathione. This assembly has been coated on a U-shaped sensor probe. Experimentally, glutathione increases Pb ion binding capability with chitosan, resulting in lower LOD. This technique has LOD 1.3 ppb with a sensitivity of 0.28 mV/ppb (Boruah, 2018). A liquid crystal-based optical platform was utilised in the detection of Pb. $NiFe_2O_4$ NPs were synthesised using the chemical co-precipitation method. The surfactant stabilised magnetic NPs were incubated in a liquid crystal (LC) based sensor system to detect Pb^{+2} ions. The bright to dark transition of LC was observed through an optical microscope. When this system was further immersed with a solution containing Pb^{2+} ions, it caused the homeotropic to the planar orientation of LC. This interaction is attributed to abundant hydroxyl groups in M-OH, Fe-OH on the surface of spinel ferrites nanoparticles. This sensor showed higher selectivity towards Pb^{2+} ions. The detection limit was estimated to be 100 ppb (Zehra, 2018). It is reported that the feasibility of nitrogen-vacancy centre nanodiamonds (NV-ND) was utilised as a potential fluorescent sensor for selective detection and determination of Pb ions in aqueous solutions. The detection and determination of the presence of Pb ions were evaluated through the change in the fluorescence intensity of (NV-ND) particles with two particle sizes (70 and 140 nm) and at pH values varied from 4 to 9. The sensor showed high sensitivity toward the Pb ions in the water sample, among other metal ions. The Pb^{2+} ion detection limit was recorded at 1.7 x 10^{-3} mM in the concentration range up to 0.2 mM. The proposed method was applied successfully to determine Pb ions in various water samples(Darwish). Dye/ionophore/Pb^{2+} co-extraction and effective water phase de-colourisation were utilised for sensitive Pb measurements and sub-ppb naked-eye detection. A low-cost ionophore Benzo-18-Crown-6-ether was used, and a simple test-tube mix and a separate procedure were developed. Instrumental detection limits were in the low ppt region (LOD=3, LOQ=10), and naked-eye detection was 500 ppt(Hakonen and Strömberg, 2018). A highly selective fluorescent sensor was reported based on the PET mechanism containing bis(2-pyridylmethyl)amine group as a binding moiety. The compound provided a sensitive (a detection limit of 3.9 µg/l in water) and single-agent fluorescence method for the assay of Pb^{2+} in pH 7.0 aqueous solution(Wu, 2006). A maleic acid (MA) functionalized AuNP coated, eFBG sensor, capable of detecting Pb metal ion in water was reported. The self-assembled carboxylic group in MA-AuNP shows an assertive coordination behaviour towards Pb^{2+} for selective detection through a Bragg wavelength shift. The LOD is found to be 10 fM with a dynamic range up to 100 nM, which was within the acceptable limit stipulated by the WHO for safe drinking water (10 ppb). The sensor's recovery concentration is > 90% for spiked real water samples. A good reproducibility (standard error < 10 pm) and specificity along with portability, small footprint and the real-time response were achieved using e-FBG sensor, showing it to be an ideal optical probe for drinking water (Vajresh K. N., 2022). MicroLaser-induced breakdown spectroscopy (micro-LIBS) integrated with laser-induced fluorescence (LIF), and this combination, laser ablation laser-induced fluorescence (LA-LIF), has achieved higher sensitivity than traditional LIBS. This study uses a 170 µJ laser pulse to ablate a liquid sample to measure the Pb content. The plasma created was re-excited by a 10 µJ laser pulse tuned to one of the lead resonant lines. Upon optimisation, the 3σ limit of detection was 35 ± 7 ppb, which is close to the EPA standard for the level of Pb allowed in drinking water (Loudyi, 2009).

Technology readiness level (TRL)

Most of the sensors for water quality monitoring demonstrate TRLs from basic scientific (TRL1) up to technology demonstration level with functional prototypes and representative models (TRL6). Consequently, more efforts are needed to bring sensor prototypes into real scenarios and demonstrate point-of-care (PoC) testing (TRL7). Once the sensor technology reaches the required standards and quality according to final users and environments (TRL8), it will be ready for implementation (TRL9). Requirements to reach higher TRLs in sensing technology are, for instance: the evaluation of ageing effects on long-term performance; reduced sensor drift; improved stability, repeatability, accuracy, calibration, and shelf life; and implementation of standards. Furthermore, regulations and legislation must be considered and revised before and during sensor design, depending on the application. For example, standards have played a crucial role in the successful commercialisation of sensing technologies and processes in industries, and standards were identified as one of the critical success factors for commercialisation. The technology can be successfully commercialised only if interlocutors and final users are intimately involved in creating standards for the commercialisation process. Commercial success will require coordinated efforts among these contributors (Zheng, 2021).

Arsenic removal devices with TRL level 7 have been developed based on different working principles; Very few plants could show satisfactory performance at the field level, both in terms of arsenic removal efficiency and in sustainable running. The major setbacks, with most of the devices, remain with the operation, maintenance, replacement and removal of used filters. The available arsenic removal technologies require refinement to make them suitable and sustainable for their large-scale effective uses (Ghosh, 2009). The Optical fibre sensor (OFS) itself could be classified at level 4. In the TRL scale, the acoustic sensor (TUSHT) itself could be classified at level 8 (Paumel, 2013). Reagent-based sensors have been deployed to measure nitrate, nitrite, phosphate, silicate, iron, and pH. These sensors use microfluidics and optics combined in an optofluidic chip with electromechanical valves and pumps mounted upon it to mix water samples with reagents and measure the optical response with the sensors reaching TRL 7 (Mowlem, 2021) .

Agrochemicals

Pesticides

Agriculture has been glorified with intensified production since the green revolution, and this has been possible due to the overuse of fertilizers, pesticides and various other modern approaches. Among these, pesticides' injudicious usage for controlling insects, bacteria, weeds, nematodes, rodents, and other pests has created toxic pesticide residues. Moreover, the persistency enhances its longevity, and sometimes it enters into the soil, plant and even the human food chain, causing severe health issues.

The pesticides belong to a category of chemicals used worldwide as insecticides, herbicides, fungicides, rodenticides, molluscicides, nematicides, and plant growth regulators to control weeds, pests and diseases in crops health care of humans and animals. The percentage chemical composition of insecticides and usage in India and worldwide is depicted in Figure 12. In India, insecticides account for the most considerable consumption rate (76 %), followed by herbicides (10 %) and fungicides (13 %). The most predominant insecticides, such as organochlorine (OC) and organophosphorus (OP), have been extensively used in India for agriculture and public health. Organochlorine insecticides like DDT, endosulfan, dioxin, HCH, and aldrin, has been found to cause some environmental or human health hazard (Bharadwaj, 2015).

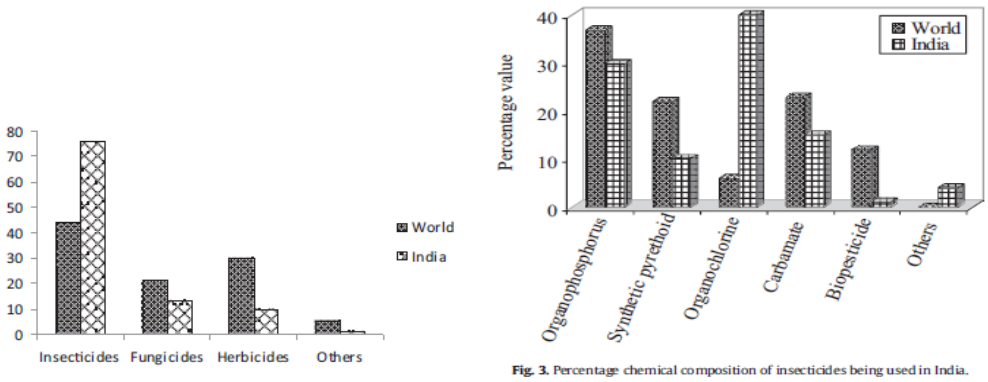


Figure 12. (a) Comparison of pesticide usage in India and worldwide (Bharadwaj, 2015) (b) Percentage chemical composition of insecticides being used in India and worldwide (al., 2015)

The excessive use of these pesticides has targeted other living creatures (e.g., fishes, birds, and humans) as well, in addition to pests/insects. Apart from soil health, naturally available biological organisms for pest control, adjoining vegetation and chronic effects on human health were observed due to pesticides in environmental systems. Common human health disorders are immune system problems, hormonal problems, delusion, reproductive problems, and even cancer. Similar human health problems were also reported by some other researchers, such as cancer, kidney and immune system problems, male and female infertility, hormonal disorders, and neuron disorders. Moreover, children also report behavioural disorders due to prolonged poisoning from pesticide residues. According to the researchers, the extent of human health problems due to pesticide poisoning can be categorized into mild or moderate (e.g., headache, dizziness, gastric problems, lack of sensation, weakness, hyperirritability, flu, itchiness of the skin, unclear vision, and neurological problems) and severe (e.g., paralysis, loss of sight), and sometimes death (Srivastav, 2020). Table 26 gives details on the biological effects of the different available insecticides.

Table 26. Classification of pesticides with their biological effect

Class	Group	Chemical name	Target sites / Efeects
Insecticides	Organo Chlorates	DDT	Liver and lungs Reproductive System Immune system
		Hexachlorohexane	Immune System Liver Blood dyscrasias anemia Reproductive system
	Organo Phosphateas	Chlorpyrifos	Immune System AChE activity in devoloping fetus Mammalian cell cultures Neurodevolopment disorder
		Methyl Parathion	Neurotoxic Effect (CNS)
		Malathion	Reproductive system AChE activity Lipid Peroxidation Genotoxic effects
	Pyrethriods	Allerthrin,Permethrin	Neurotoxic effects and Na^{+} and K^{+} channels
Fungicides	Carbamates	Aldicarb,Carbryl propoxur	Nervous System
	Dicarboximide	Mancozeb	Endocrine disruptor
	Dithiocarbamates	Vinclozolin,Asomate,Amobam	Antiandrogenic effects
	Organomercuricals	Methyl Mercury, Phenyl mercuric acetate	Central nervous system
Herbicides	Sulfonylureas	Chlorosulfuran	Embryo Devolopment
	Cholorophenoxy compouds	MCPA, MCPP, 2,4-D	Human carcinogens

Continuous overexploitation of pesticides is becoming a grave problem in the ecosystem because of its persistent nature, acute and chronic toxicity, and potential hazardous health dysfunction. Therefore, pesticide analysis has become an essential tool to understand the implications of environmental pollution and the optimal usage of pesticides as preventive steps. Pesticides were usually analysed using conventional techniques like gas chromatography (GC), high-performance liquid chromatography (HPLC), and other spectroscopic methods. These analytical methods involve laborious procedures performed by highly trained technicians, undergo cleanup steps that increase analysis time and the risk of errors, and are not convenient for on-site or on-field detection of multiple analytes detection simultaneously. So, the recent trends shifted towards biosensors in pesticide residue detection in various samples (water, soil and agriculture product extracts etc.) (al., 2019).

Biosensors have been directed mainly towards health care, environmental applications, food industry, and agricultural practices as an alternative to conventional analytical techniques. Biosensor technology is used for the direct, fast, and easy determination of various pesticides (organophosphates, organochlorides, organocarbonates, etc.). Based on the different transducers, namely optical, electrochemical and piezoelectric sensors have been predominantly reported in Table 27 (al., 2020b).

Table 27. Biosensor technology for detection of pesticide residues

Analytes	Sensor types	LOD (ng/L)	Waterbodies
Picloram	Bioelectrochemical	5	Paddy field water
Malathion	Biosensor	1	Tap water
Methamidophos	Biosensor	0.01	Tap water
Monocroptophos		0.013	River water
Mevinphos		0.009	
Phosphamidon	Bio sensor	0.012	River and Tap water
Omethoate		0.032	
Benzatone	Electronical	262.3	River water
Carbayl	Electrochemical	5.3	Wastewater

Heptenophos	Electrochemical	3.6	
Fenitrothion		160	
Carbofuran	Electronical	2	Tap and Farmland water
Fenobucarb		2	
Paraoxon	Bioelectronical	2.8	Lagoon Water
Carbaryl		8.0	
Chlorpyriphos	Biosensor	0.004	Lake water
Chlorfevinfos	Bio sensor	0.004	
Atrazine	Electrochemical	2.2	River water
Atrazine	Electrochemical	4.5	River water
Atrazine	Electrochemical	1.9	River water
Atrazine	Electrochemical	13	River water
Ametryne	Electrochemical	3.1	River water
Atrazine	Electrochemical	30.2	Natural Water
Chlorpyrifos		1.1	
Paraoxon	Bioelectronical	30	River Water
Malaoxon		25	
Chlormequat	Bioelectronical	502.74	River and Ground Water
Carbofuran	Bioelectronical	20	Well water
Carbaryl		300	
Paraoxon	Bioelectronical	5.5	Well water
Methyl Parathion		5.8	
Omethoate	Bioelectronical	21.3	Lake Water
Atrazine	Biooptical	0.15	Drinking, lake and agricultural waste water
Isoproturon	Bio-optical	3	Well water
Carbaryl	Bio-optical	0.029	Drinking water
Carbendazim	Bio-optical	68	Environmental Water
Benomyl		35	

Carbaryl	Bio-optical	6	River, Well , Dam and irrigation water
Metsulfuron methyl	Optical	0.14	River , well and irrigation water
α- Naphthol		2	
O-Phenylphenol	Optical	2	Tap and River water
Triazine	Bio-optical	0.0013	River water
Thiabendazole		2.5	
Metsulfuron methyl	Optical	3.3	Well, river and irrigation water
N-1-Napthylphthlamic acid	Optical	8.1	Drinking and mineral water
Linuron	Bio-optical	130	Tap, underground, mineral and river water.
1- Napthylamine		11.2	
Thiabendazole	Optical	4.5	Tap, underground, mineral, and river water.
Carbaryl	Bio-optical	1.38	Groundwater, tap and river water
1-Napthylamine	Optical	1.1	Well, tap and urban waste water
Paraquat	Optical	0.11	Tap, well, lake, river and rain water
Paraquat	Optical	1.6	Wastewater
Paraquat	Optical	0.003	Tap, mineral, waste and ground water
Paraquat	Bioelectrochemical	0.926	River and Ground water
Paraquat	Bio-optical	0.036	River water
Paraquat	Electronical	23.92	River Water
Paraquat	Electronical	2	Dam,River and Tap water
Paraquat	Optical	22	River , dam and mineral water
Paraquat	Ele-Optical	0.2	River water

Diquat	Ele- optical	0.1	Ground and bog water
Dipterex		5.152	
Paraquat	Che-optical	5.143	Wastewater
Paraoxon	Optical	0.05	Tap and River water
Diniconazole	Bio-optoical	6.4	River and waste water
Diuron	Electrochemical	0.00125	Lakewater
Iprobenfos	Bio-optical	53.6	River water
2,4D	Bio-electronical	50	River water
Diazinon	Bio electrochemical	0.039	River wastewater
Metamitron	Electrochemical	7.28	River water
Carbamate	Bio-optical	3.3	Lake water
Diuron	Bio-electrochemical	2.1	River water
Mesotrione	Electrochemical	8.822	Lake and tap water
Paraquat	Electrochemical	3.086	River water
Fenoxanil	Electronical	0.0092	River water
Parathion methyl	Bio electrochemical	0.02	Tap and river water
Monocrotophos	Bio-electrochemical	0.01	Tap and river water
Didoran	Bio-electrochemical	0.099	Tap and river water
Fenitrothion	Electrochemical	0.036	Tap water and lake water
Carbamate	Optical	0.023	River Water
Fenoxycarb	Bio-optical	949.221	River water
Malathion	Ele-optical	0.0991	River water
Methomyl	Electronical	126.192	River and tap water
2,4,D	Electronical	26.405	Lake and well water
Pyrethroids	Bio-optical	42.64	River water
2,4-D	Electronical	44.008	Riverwater
Fomesafen	Electrochemical	89	Lake water
Imazethapyr	Bio-optical	578	Lake water
Dichlorophen	Electrical	3.768	River water
Hexazinone	Bio electronical	0.00066	River water

Malathion	Optical	1.84 X 10^{-7}	Agricultural run off and lake water
Fenitrothion	Optical	1.677	Well, river and tap water
Pendimethalin	Electronical	10.408	Tap and river water
Methol	Electrochemical	0.344	River water
Azinphos methyl	Che-optical;	0.549	Tap and river water
Fenvalerate pyrethroid	Optical	291.3	Lake water
Propham	Electrochemical	0.789	River water
Propham	Electrochemical	0.179	River water
Cyanazine	Electrochemical	0.06	Tap, river and ground water
Tau-fluvalinate	Bio-optical	6.105	Lake water
Methyl- parathion	Optical	291.3	Lake water
Pymetrozine	Optical	2.172	Tap and lake water
Imidadoprid	Electronical	106.1	River water
Pyrethriod	Bio-optical	6.568	River water
Paraquat	Electronical	0.8	River water
Clopyralid	Electrochemical	0.154	River water
Carbendazim	Electronical	37.473	River water
Quinalphos	Electrochemical	0.378	Tap and lake water
Methyl parathion	Bio-optical	1.87	River water
2,4-D	Optical	0.0045	Tap, bottle and lake water
Diethofencarb	Electronical	320	River water
Diazinon	Bio-electrochemical	57.827	River water
Naptalam	Electrochemical	4.37	River water
Phosmet	Bio-optical	.0004	Lake water
Phoxim	Che-optical	298.298	River water
Bentazone	Electrochemical	8.918	Lake and ground water
Fenitrothion	Electronical	0.155	Well water

Chlorpyrifos	Bio electrochemical	0.07	Lake water
Lindane	Ele-optical	0.585	River and tap water
Difenzoquat	Electro chemical	102.225	River and deionized water
Diquat	Electrochemical	37.844	River and drinking water
Methyl parathion	Optical	27.674	Pond water
Glyphosate	Optical	5.07	Lake water
Lindane	Opto - electrochemical	40.716	River water
Glyphosate	Optical	845	River water
Methyl parathion	Electrochemical	0.012	River water
Amitrole	Electrochemical	58.856	River water
Methhamidophos	Optical	0.017	Tap andriver water
Fenitrothion	Electronical	0.0526	River water
Carbendazim	Electrochemical	5.736	River water
Ofloxacin	Optical	0.123	River and tap water

Fertilizers

Chemical fertilizers, mainly nitrogen (nitrate, nitrite), ammonium and phosphate, etc., are used extensively in modern agriculture to improve crop yield. Because the prolonged application of these chemical fertilizers tends to promote agricultural soil health deterioration and groundwater and surface water contamination, causing a major environmental and public health concern. Environmental nitrogen and phosphorous contribute to eutrophication, which leads to oxygen depletion and thus results in aquatic animals' death. Moreover, a high nitrogen concentration contaminates the drinking water can cause nitrate poisoning.

Therefore, high concentrations of nutrients have been identified as a potential cause of colorectal cancer and non-Hodgkin's lymphoma. As a result, researchers have an intense desire to build innovative devices to monitor aquatic nutrient concentrations in a timely fashion reliably, thus providing valuable information that can guide sustainable use and remediation, with optical and electrochemical sensors being the most popular.

Nitrogen (Nitrate and Nitrite)

As nitrate fertilizers are increasingly used in agriculture, the quantity of nitrate leaching from fields into rivers and groundwaters increases cumulatively. An elevated level of nutrients in natural waters can lead to environmental consequences such as increased phytoplankton growth and eutrophication, increased water turbidity, diminished dissolved oxygen, changes in biodiversity and ultimately disruptions to ecosystem function.

Nitrate is a permitted food additive for curing meat since it is not toxic to humans. However, once nitrate has entered the body, it can be reduced to nitrite by bacteria in the stomach and further incorporated into carcinogenic N-nitrosamine compounds (al., 2020d).

Nitrates (NO_3^-) and nitrites (NO_2^-) are frequently present in plants, soils and waters; since their chemistries are practically in dissociable, one is rarely found without the other. If in excessive levels, these ions can have an adverse impact on public health and ecological systems. Nitrite is the foremost toxic agent, but the fairly inert nitrate is easily reduced to nitrite by bacterial action in the soil or within the digestive system.

In humans, methemoglobinemia is the principal adverse health effect caused by excessive nitrates/nitrites intake. Nitrite can irreversibly oxidise haemoglobin to methemoglobin which is unable to bind oxygen, causing clinical cyanosis among other symptoms. Infants are particularly susceptible to nitrite induced methemoglobinemia, often referred to as the *blue-baby* syndrome; a small number of fatal cases has been reported, generally associated to the consumption of water resources that failed drinking water standards. Concern has been raised on the potential role of nitrite in forming carcinogenic *N*-nitroso compounds (NOCs) via reaction with secondary amines. Although many NOCs have been shown to be genotoxic in animal models, the relationship between nitrites/nitrates intake and the risk of cancer in humans has not been unequivocally proved so far. No matter the controversy, the information generated from the analytical surveillance of nitrite in food products is fundamental for the management of health risks (Almeida, 2010).

Numerous analytical assays are available for nitrite, nitrate, and phosphorus quantification in water samples using UV-Vis spectrophotometry, ion chromatography, polarography, capillary electrophoresis, gas chromatography, and mass spectrometry (GC-MS) or fluorescence spectrophotometry. In these methods, the major drawbacks include the risk of water alteration during sampling, storage, transportation, and manipulation, the need for hazardous chemicals and pre-treatments with associated environmental footprints, as well as an inevitable delay in the provision of the analytical data, sample pre-treatment, susceptibility to matrix interferences, insufficient detection limits, long time of analysis. This situation has challenged analytical sciences to develop innovative and improved tools, leading to the budding field of biosensors based on electrochemical and optical transducers for nitrite, nitrate phosphorus and ammonium (Almeida, 2010).

Table 28 gives a detailed comparison of the different sensing techniques for nitrate sensing.

Table 28. Different technologies for nitrate sensors

Transduction System	Sensing element/ Structure	Detection limit(μM)	Detection range (μM)	Key findings	Ref.
Potentiometric	reduced graphene oxide (rGO)/TEBAC	0.08	0.045- 4.5	High sensitivity and selectivity. Suitable for real time detection	(Chen, 2018)
Potentiometric	Ag-modified carbon Ag-UMEs	3.2-5.1	$4\text{-}10^3$	Real time detection	(Zhad, 2015)
Potentiometric	Co(II)-composed PVC membrane	3.98	$10\text{-}10^5$	Tested for tap, mineral and river water	(Pietrzak, 2020)
Amperometric	Nanorod of Co immobilizedNR and PEDOT	2.5	3.2-17.7	Easy processabilty and high stability Very rapid response Low back ground noise	(Gokhale, 2015)
Voltametric	Cu/MWCNT/rGO glassy carbon electrode	0.1	$1\text{-}10^3$	Stable High selectivity And sensitivity	(Bagheri, 2017)
Volatmetric	Nanowire -based Cu electrodes	1.35	8-5860	Stable and porous structure Wide range	(Liang, 2016)
Voltametric	PEG-SH coated carbon paper Functionalised with AuNPs and SePs	0.016	16-5000	Tested for lake water Dual function sensor(for $NO_3^-$and Hg^{2+}) Inexpensive, robust and disposable	(Bui, 2016)
Optical	UV Raman spectrometer Orizon OPO	40	16-1600	On-line monitoring Inexpensive	(Sterzi, 2019)

Optical	Fiber optic SPR probe Cu-NPs/CNT	NA	2.5-10^3	Simple structure Suitable for remote multiparameter measurement	(Zhang, 2019d)
Optical	Optical microfiber	2.74	0-19 X10^3	Tested for sea water Suitable for in situ detection Easy to construct and cheap	(Yang, 2020)
Optical	Deep UV LED detector	0.64	1.6-1.2X10^3	Tested for tank water , waste water and fresh water Suitable for in situ detection Inexpensive	(Murray, 2020)

Phosphates detection sensor

Phosphates can exist in wastewater in several forms depending on the source/nature of the discharge but are generally grouped within three broad classes: orthophosphates, condensed phosphates (pyro-, meta- and poly-) and organic phosphorus. Approximately 50-70% of the phosphate in wastewater exists as orthophosphate (PO_4), which could be in the form of phosphoric acid (H_3PO_4), dihydrogen phosphate ($H_2PO_4^-$), hydrogen phosphate (HPO_4^{2-}) and phosphate ion (PO_4^{3-}). From an environmental perspective, the concentration of phosphate in water is crucial due to its role in eutrophication.

Traditionally phosphate was monitored manually by collecting and filtering samples later analysed in a laboratory. Various detection strategies for phosphate include phosphate ion-selective electrodes based on potentiometric techniques, indirect voltammetric detection based on the reaction of phosphate with various metals and associated complexes, and the development of sensors exploiting enzymatic reactions. Many studies have shown the feasibility of phosphate analysis in water using electrochemical or optical transducer sensors (Almeida, 2010). Table 29 gives a detailed comparison of the different sensing techniques for phosphate sensing.

Table 29. Different technologies for phosphate sensors

Transducing System	Sensing element/ Structure	Detection limit(μM)	Detection range (μM)	Key findings	Ref.
Potentiometric	PTFE-Ag_3PO_4-Ag_2S	5.45	10-10^5	High stability pH independent response(5-8) sample preparation	(Bralić, 2018)
Potentiometric	CuMAPc-PnBA coated Au electrode	1X10^{-3}	4X10^{-3}-10^4	Tested for tap, river, underground and drainage water pH independent response High sensitivity	(Abbas, 2016)
Potentiometric	PyO-ZnO NR array	0.5	1-7000	Wide detection range High sensitivity	(Ahmad, 2017)
Potentiometric	Mo electrode	1.9	10-10^5	Suitable for on-line analysis pH independent response variable response time in different concentration	(Li, 2016)
Potentiometric	Nano IIP/CPE	4	10-10^5	pH dependent response High selectivity	(Alizadeh, 2018)
Potentiometric	NiO/NiOOH-PrC electrode	1	1-10^5	High sensitivity, durability and reusability Inexpensive Rapid on-site analysis	(Sedaghat, 2019)
Potentiometric	Al_2O_3-rGO	0.105	263-1.05	Tested for waste water Inexpensive and miniaturized sensor Suitable for real time detection	(Zhou, 2020)
Amperometric	CBNPs-modified SPE	6	Up to 10^6	Suitable for online analysis Fouling resistance High selectivity	(Talarico, 2015)

Amperometric	CPE working vs Ag/AgCl Reference electrode	0.3	1-20	Tested for sea water Usable for small sample volume High selectivity	(Quintana, 2004)
Amperometric	Ag/rGO-FET	0.2	5-6 X 10^3	Tested for lake water Long term stability Inexpensive User friendly and easily scalable	(Bhat, 2019)
Optical	TP3-Cu Complex	8.7X10^{-3}	NA	Coupled to the selective fluorescent quenching of TP3 by Cu (II) High selectivity towards biological phosphates	(Sam-Ang, 2019)
Optical	Euj@BUC-14	0.88	5-150	Tested for tap water High selectivity towards PO_4^{3-} pH independent	(Zhang, 2019c)
Optical	PBP-MDCC complex	0.01	0.01-0.67	Disposable wax printed paper Connected to smart phone sensing apparatus High selectivity towards inorganic Phosphates(Pi)	(Sarwar, 2019)
Optical	Ceteareth 25 - AgNps	0.076	2-240	Tested for drinking water High selectivity towards PO_4^{3-}	(Salem, 2021)
Optical	Tb-MOF-Zn	4X10^{-3}	0.01 -200	High selectivity towards PO_4^{3-}	(Fan, 2020)
Optical	UV LED Photodiode detector	0.09	0.09-50	Tested for freshwater Suitable for in-situ detection	(Donohoe, 2018)

Ammonia detection Sensor

Ammonia nitrogen (ammonia or ammonium) is widely present in natural waters and significantly affects aquatic flora and fauna. It plays a crucial role in human production, health, and ecosystem stability.

Ammonium (NH_4^+) or its uncharged form ammonia (NH_3) — is a form of nitrogen that aquatic plants can absorb and incorporate into proteins, amino acids, and other molecules. High concentrations of ammonium can enhance the growth of algae and aquatic plants. Bacteria can also convert high ammonium to nitrate (NO_3^-) in nitrification, which lowers dissolved oxygen.

Un-ionised ammonia is a toxic form and predominates when pH is high. The NH_4^+ ion is relatively non-toxic and predominates when pH is low. In general, less than 10 % of ammonia is toxic when pH is less than 8.0 pH units. This proportion increases dramatically as pH increases. The equilibrium between NH_3 and NH_4^+ is also affected by temperature. More toxic ammonia is present in warmer water than in cooler water at any pH.

Many detection methods, including spectrophotometric methods and ion-selective electrodes, have been developed to analyse ammonia nitrogen in the water. Recent developments in optical and electrochemical detection systems for aqueous ammonia nitrogen are shown herein (Almeida, 2010, al., 2020a).

Table 30 gives a detailed comparison of the different sensing techniques for ammonia sensing.

Table 30. Different technologies for ammonia sensors

Transducing System	Sensing element/ Structure	Detection limit(µM)	Detection range (µM)	Key findings	Ref.
Potentiometric	PpyCOSANE-Au	40	NA	Tested for tap water and sewage Integrated to passive lab on chip system Suitable for real time analysis	(Gallardo-Gonzalez, 2019)
Amperometric	AlaDH-f-MWCNT/SPE	1	$50 - 5 \times 10^5$	Tested for tap lake and river water. Increased surface area Improved output current and electrochemical sensitivity	(Dave, 2017)

Voltametric	Nano-Pt micro electrode	45	45-6.4 X 10^4	Simple and inexpensive preparation Long term stability	(Ning, 2017)
Conductometric	Calixarene-Au electrode	10	10-1500	Tested for river water pH dependent response High selectivity	(Saiapina, 2016)
Impedometric	FG-SPE	0.0044	10^{-6}- 0.1	High sensitivity and reasonable Selectivity Rapid response Reversible ammonia response	(Tadi, 2016)
Optical	PDMS-thymol/nitroprusside composite	22.2	5.55-83.3	Tested for river water and waste water Portable and rapid sensor Useful for onsite detection	(Prieto-Blanco, 2015)
Optical	BP flower extract paper	118	294-2941	Green and inexpensive Smartphone based detection	(Jaikang, 2020)
Optical	MB@AuNP	24	57.7-769	High selectivity towards AP Inexpensive and easy to use sensor	(Keskin, 2020)
Optical	LDR sensor Mo-blue method	14.9	16.6-221.7	Tested for fresh water Highly sensitive and reproducible Inexpensive and portable	(Khongpet, 2019)

Gaps Identified in agrochemicals

- Literature studies related to agrochemicals (fertilizers and pesticides) detection in water reveal that more than 95 % of it falls under the TRL-3 level and predominantly uses electrochemical transducer methods.
- In India, very few studies were done on agrochemicals, especially pesticides detection in water for water quality.
- At present, there are no field-deployable water quality monitoring systems commercially available to monitor agrochemicals sensors in ground & surface water in India; and portable devices to analyse these pesticides level in low resource settings.

- Current measurements of pesticides in water are mainly based on off-line monitoring and imply low-frequency data sampling and delay between sampling and availability of the results.
- Real-time monitoring of wastewater quality remains an unresolved problem in the wastewater treatment industry.
- Advanced autonomous platforms capable of performing complex analytical measurements at remote locations still require individual power, wireless communication, processor and electronic transducer units, along with regular maintenance visits. Therefore, there is a need to develop an automated, cost-effective method of wastewater quality monitoring, particularly for the measurement of agrochemicals (Fertilizers and Pesticides).

Antimicrobial Resistance (AMR) sensors

According to the World Health Organization (WHO), antimicrobial resistance occurs when bacteria adapt and grow in the presence of an antimicrobial (AM) agent (WHO: Geneva, 2015). It can also be described as a phenomenon when microorganisms (bacteria, viruses, fungi, and parasites) are no longer affected by an AM to which it was previously sensitive, as a result of mutation of the microorganism to evade the effect of the antimicrobial or of the acquisition of the resistance gene (Boolchandani, 2019; Christaki, 2020). The WHO published a list of priority pathogens resistant to antibiotics; on this list, 12 families of bacteria are selected for the research and development of new antibiotics due to the growing need for innovative treatments against multi-resistant bacteria in hospital environments (Reynoso, 2021)

Table 31. Different types of phenotypic sensor (Reynoso, 2021)

	Target	Antibiotic	MIC (μg/mL)	LOD	Ref
Asynchronous magnetic bead rotation	E. coli	Gentamicin	1	Single bacterium binding events	(Sinn, 2011)
Atomic force microscope cantilevers	E. coli	Ampicillin	12.5–50	NM, 1×10^5 CFU/mL **	(Bennett, 2020)
Brownian motion	P. aeruginosa	Gentamicin	2	One bacterium	(Chung, 2016)
Spectral amplitude modulation MZOQCM	S. epidermidis	Ciprofloxacin Oxacillin Ciprofloxacin	0.5 1 1	1×10^5 CFU/mL	(Wu, 2020)
biomaterial microcantilever with an embedded microfluidic channel	E. coli	Ampicillin Kanamycin	NM	1×10^5 CFU/mL **	(Etayash, 2016)
Colorimetric	E. coli	Ampicillin	128	10 CFU/mL	(Kadlec, 2014)
SPR	E. coli, P. aeruginosa	Carbenicillin Gentamicin Rifampicin	100 1 Resistant	NR	(Thrift, 2020; Groome, 2020)
laser-patterned paper-based	E. coli	Amoxicillin	30	2.5×10^9 CFU/mL	(He, 2020)
SERS	L. lactis	Ampicillin Ciprofloxacin	NR	NR	(Wang, 2016)
Raman tweezers	S. aureus	Oxacillin	2000	10^{12} cells/L	(Bernatová, 2021)
DPV	S. gallinarum	Ofloxacin Penicillin	32 16	10^2 CFU/mL	(Ren, 2020)
Capacitance	E. coli *, A. baumannii, P. aeruginosa, K. pneumoniae, S. aureus, E. faecalis	Amikacin Ampicillin Aztreonam Cefepime Cefotaxime Ceftazidime Gentamicin	≤2 ≥32 ≤1 ≤1 ≤4 ≤1 ≤1	10^5 CFU/mL **	(Lee, 2020)
Impedance	E. coli, S. aureus	Erythromycin	0.1	10^3 CFU/mL **	Safavieh, 2017)

Current caused by varying pH values	E. coli	Kanamycin Cefotaxime Ofloxacin	1–4 0.1–6 5	Single cells	(Ibarlucea, 2017)

** Initial concentration; CFU, colony-forming unit;; NM, not measured; NR, not reported; MIC, Minimum inhibitory contribution; * Antibiotic and MIC correspond to E. coli; DPV, differential pulse voltammetry; SERS, surface-enhanced Raman spectroscopy

Methods for AMR detection based on sensor and biosensors can be classified as phenotypic and genotypic. The phenotypic techniques consist of detecting the expression of the microorganism's resistance mechanisms. Genotypic techniques allow the detection of genes that express some mechanism of the microorganism resistance to the action of the antimicrobial (Reynoso, 2021). Magnetic, mass, mechanical, thermal, optical, and electrochemical sensors are used to monitor AMR and some of these sensors have been tabulated in Table 32.

Table 32. Different types of genotypic sensors (Reynoso, 2021)

Technique	Target	Type of resistance	LOD	Ref
Electrochemical-EIS and CV	rpoB	Rifampicin resistance	0.08 fmol/L	Bizid, 2018)
Electrochemical—capacitance	ampR	Ampicillin resistance	1–4 pM	(Liu, 2015)
Electrochemical—DPV	MDR1	Multidrug resistance	2.95 × 10−12 M	(Peng, 2015)
Optic—fluorescence	CTX-MNDM-1	Cephalosporins resistanceCarbapenems resistance	<10 copies of the gene	(Hu, 2017)
Optic—SERS	tetA	Tetracycline Resistance	25 copies/μL	(Lu, 2020)
Optic—fluorescence	lamB	Increases resistance to chlortetracycline, ciprofloxacin, balofloxacin and nalidixic acid	4–250 pM amplicon concentrations	(Koets, 2009)
Mechanic—piezoelectric	mecR	Methicillin resistance	0.125 μM	(Tombelli, 2006)

CV, cyclic voltammetry; DPV, differential pulse voltammetry; EIS, electrochemical impedance spectroscopy;

Commercially available sensors

Table 33. Commercially available sensors

Company	Detection technique	Features	Link
The UtiMax Lab Automation System of Genefluidics Inc. (Duarte, CA, USA)		Automated diagnostic platform Robotic liquid handling systems Disposable sensor array chips	https://www.genefluidics.com/genefluidics-announces-ce-ivd-marking-of-utimax-uropathogen-identification-id-and-antimicrobial-susceptibility-testing-ast/
Vitek systems (BioMèrieux)		Integrate fast and actionable diagnostics, expert consultancy services, and advanced analytic platform	https://www.biomerieux-usa.com/solutions/healthcare-solutions/antimicrobial-stewardship
BD Phoenix instruments, UK		Unmatched Real MIC Quality Results Fast and Accurate Resistance Detection Panel Flexibility (Combo, ID only, AST only)	https://www.bd.com/en-uk/products/diagnostics-systems/identification-and-susceptibility-systems/phoenix
Alfred 60AST system (Alifax)		Perform bacterial culture, RAA and susceptibility testing by automating the whole process of sample inoculation, reading and result transmission	https://www.alifax.com/products/bacteriology-line/show/alfred-60
MicroScan WalkAway system (Beckman Coulter		Gold-standard accuracy, Simultaneous processing, efficient high-volume testing. Single, automated platfom	https://www.beckmancoulter.com/es/products/microbiology/microscan-walkaway-plus-system

Gaps:

1. Commercially available tools are at the development stage and have not met the validation requirements due to amplification necessity of the real samples for detection of the extremely low concentrations of the target samples.
2. Low initial pathogen number and the presence of contaminating sample matrices have made integration of many different technologies a necessity and expensive

Biological contaminants- Pathogens

Pathogens are key contaminants in water responsible for the generation of various water-borne diseases, including viruses, fungi, bacteria, and protozoan parasites. The pathogenic effects of these species in water depend on their shape, size, composition, and structure. The resulting water-borne diseases are a severe threat to the environment, including humans and animals, and are directly responsible for environmental deterioration and pollution. Several deferent types of pathogens have been detected in diverse irrigation water sources, including bacteria (e.g., Salmonella and Escherichia coli), protozoa (e.g., Cryptosporidium and Giardia), as well as viruses (e.g., noro viruses) (al., 2018). Some of the crucial pathogens with their associated disease and relative infectivity have been identified in Table 34.

Table 34. Water-borne pathogens and their significance in water supplies. Adopted from WHO guidelines

Pathogen	Associated disease	Health significan ce	Persistence in water supplies	Resistance to chlorine	Relative Infectivity
Bacteria					
Burkholderia pseudomallei	Melioidosis	High	May multiply	Low	Low
Campylobacter jejuni	Gastroenteritis	High	Moderate	Low	Moderate
Escherichia coli *Pathogenic*	Gastroenteritis	High	Moderate	Low	Low
E.coli	Gastroenteritis	High	Moderate	Low	High
Enterohaemorrhagi c	Gastroenteritis, hemolytic Uremia	High	Moderate	Low	High

Legionella spp.	Legionaires disease	High	May multiply	Low	Moderate
Non-tuberculous Mycobacteria	Pulmonary disease, skin disease	Moderate	May multiply	high	Moderate
Pseudomonas aeruginosa	Pulmonary disease, skin infection	Moderate	May multiply	Moderate	low
Salmonella typhi	Typhoid fever	High	Moderate	Low	Low
Salmonella enterica	Salmonellosis	High	May multiply	Low	Low
Shigella sp.	Shigellosis	High	Short	Low	High
Vibrio cholerae	Cholera	High	Short to long	Low	Low
Yersinia enterocolitica	Gastroenteritis	Moderate	Long	Low	Low
Viruses					
Adenoviruses	Gastroenteritis, Respiratory infection	Moderate	Long	Moderate	Low
Enteroviruses	Gastroenteritis	Moderate	Long	Moderate	High
Hepatitis virus A,E	Hepatitis	High	Long	Moderate	High
Norovirus	Gastroenteritis	High	Long	Moderate	High
Sapoviruses	Gastroenteritis	High	Long	Moderate	High
Rotaviruses	Gastroenteritis	High	Long	Moderate	High
Protozoa					
Acanthamoeba spp.	Keratitis, Encephalitis	High	May multiply	Low	High
Cryptosporidium parvum	cryptosporidiosis	High	Long	High	High
Cyclospora cayetanensis	Gastroenteritis	High	Long	High	High
Entamoeba histolytica	Amoebic dysentery	High	Moderate	High	High
Giardia Intestinalis	Giardiasis (Beaver fever)	High	Moderate	High	High

Naegleria fowleri	Primary amoebic meningoencephalitis	High	May multiply	Low	Moderate
Toxoplasma gondii	Toxoplasmosis	High	Long	High	High
Helminths					
Dracunculus medinensis	Dracunculiasis(Guinea worm disease)	High	Moderate	Moderate	High
Schistosoma spp.	Schistosomiasis	High	Short	Moderate	High

The potential presence of these pathogens detection in water requires sensitive, powerful, efficient, and ideally real-time monitoring methods for reproducible quantification. Conventional methods for pathogen detection mainly rely on time-consuming enrichment steps followed by biochemical identification strategies, which require assay times ranging from 24 h to up to a week. However, in recent years, significant efforts have been made towards developing biosensing technologies enabling rapid and close-to-real-time detection of water-borne pathogens. Biosensors and sensing systems based on various transducer technologies, especially electrochemical and optical methods for water-quality monitoring, have been studied with a specific focus on rapid pathogen detection (al., 2020c). Table 35 gives a comparison of the different types of optical bio sensors.

Table 35. Different types of optical bio sensor

Type	Microorganism detected	Method	Sensitivity/detection limit	Ref.
SPR	*Salmonella*	SAM of 5′-thiolated single-stranded DNA (ssDNA) probes attached to gold surface	2 fM	(Singh, 2015)
SPR	*Listeria monocytogenes*	Antibody to the virulence factor actin polymerization protein (ActA)	$2X10^6$ $CFUmL^{-1}$	(Nanduri, 2007)
SPR	*Escherichia coli O157:H7*	AgNps-rGO composites bound to the fiber probe surface to enhance the sensitivity. Magainin as recognition element	500 CFU /mL	(Zhou, 2018a)
Evanescent wave absorbance fiber optic sensor	*E.coli*		1000 CFU /mL	(Bharadwaj, 2011)
Evanescent wave fiber sensor	*Shigella*	DNA as a bio recognition element		(Xiao, 2014)
Fluorescence sandwich assay	*E. coli*	Immunomagnetic separation based on iron oxude core, chitosan- modified quantum dots as fluorescence label.		(Dogan, 2016)
FRET	*E.coli*	AuNPs(acceptor):(UCNPS, donor)		(Jin, 2017)

Fluorescence	*Salmonella enteritidis*	Aptamer recognition and target - induced assembly of G-quadruplex DNA boud by fluorescent dye N-methyl mesoporphyrin IX		(Zhang, 2016)
Chemiluminescence	*E.coli O157:H7, Salmonella typhimurium, Legionella pneumophila*	Antibody micro arrays produced on poly(ethylene glycol)-modified glass detection via streptavidin-horse radish peroxidase reaction	3000 cells/ mL for E. coli 3X10^6 cells /mL for S. typhimurium 1X 10^5 cells/mL for L. pneumophila	(Wolter, 2008)
Colorimetric	*Salmonella, listeria and E. coli O 157*	Enzyme free immuno-assay based colorimetric detection via gold nanoparticles with cysteine as cross linker	600 molecules in 150 µL	(Bui, 2015)
Colorimetric	*E. coli*	Polyaniline nanoparticle sensitive to protons released by metabolic products of pathogenic bacteria		(Thakur, 2015)
Colorimetric	*E.coli, Staphylococcus aureus*	Colorimetric dyes , hydroxynapthol blue , calcein-based dsetcetion after isothermal DNA amplification	30 CFU/mL for E. coli and 200 CFU/mL for S. aureus	(Safavieh, 2014)

Optical fiber gratings (OFGs), especially long-period gratings (LPGs) and etched or tilted fiber Bragg gratings (FBGs), are playing an increasing role in the chemical and biochemical sensing based on the measurement of a surface refractive index (RI) change through a label-free configuration. In these devices, the electric field evanescent wave at the fiber/surrounding medium interface changes its optical properties (i.e. intensity and wavelength) as a result of the RI variation due to the interaction between a biological recognition layer deposited over the fiber and the analyte under investigation. The use of OFG-based technology platforms takes the advantages of optical fiber peculiarities, which are hardly offered by the other sensing systems, such as compactness, lightness, high compatibility with optoelectronic devices (both sources and detectors), and multiplexing and remote measurement capability as the signal is spectrally modulated. In addition, Escherichia coli (E. coli) bacteria have been identified to be the cause of variety of health outbreaks resulting from contamination of food and water. Timely and rapid detection of the bacteria is thus crucial to maintain desired quality of food products and water resources. A novel methodology proposed in this paper demonstrates for the first time, the feasibility of employing a bare fiber Bragg grating (bFBG) sensor for detection of E. coli bacteria (al., 2017). Table 36 compares the different types of biosensors, and the microorganism detected.

Table 36. Different types of biosensors and the microorganism detected

Type	Microorganism detected	Method	Sensitivity / detection limit	Ref.
Voltametric bio sensor	*E.coli*	Avidin- modified polyaniline (PANI) electrochemically deposited onto a Pt disc electrode	Target probe (0.009 ng/L) 11 e. coli cells /mL	(Arora, 2007)
Voltametric bio sensor	*E.coli*	Fullerene – PMMA substrate with immobilized DNA probe		(Shiraishi, 2007)
Voltametric bio sensor	*E.coli lac Z gene*	SAM of 3,3-dithiodipropionic acid (N-succinimidyl ester), which usually is used as a spacer, onto gold (Au) disc with DNA probe		(Loaiza, 2007)
Voltametric bio sensor	*E.coli*	Using 1-fluoro-2-nitro-4-azidobenzene modified octadecanenthiol SAM	0.5 X 10^{-18} M	(Pandey, 2011)
Voltametric bio sensor	*E.coli*	Sol- gel derived nano- zirconia (ZnO_2)platform with immobilized 17-base single stranded DNA from 16s RNA	10^{-6}-10^{6} pM	(Solanki, 2009)
Potentiometric Sensor	*Salmonella typhimurium*	Natural affinity between streptavidin and biotin	119 CFU	(Dill, 1999)
Potentiometric sensor	*E.coli O157:H7*	Natural affinity between streptavidin and biotin	2.5 X 10^{4} cells/mL	(Gehring, 1998)
Potentiometric sensor	*Bacillus subtilis*	Natural affinity between streptavidin and biotin	3000 cells/mL	(Uithoven, 2000)
Electrochemical biosensor	*E.coli O157:H7*	Bifunctional glucose oxidase (GOx)-polydopamine - bsaed polymeric nanocomposites	100 CFU/mL	(Xu, 2016)

		and Prussian blue-modified screen-printed interdigitated microcontroller		
Electrochemical biosensor	*Listeria monocytogenes*	Enzyme- linked immunosorbent assay based amperometric biosensor based on AuNP – modified screen printed carbon electrodes.	100 CFU/g of food	(Davis, 2013)

Commercially available Biosensor for Pathogen detection in water and food sample (al., 2020e) shown in *Table 37.*

Table 37. Recent publication with commercial optical pathogen sensors

Device	Analyte	Principle	LOD	Medium
Biacore	E.coli O157:H7	Polyclonal antibody	0.6 X 10^{6} CFU/mL	Buffer solution
	Salmonella enteritidis	Polyclonal antibody	1.8 X 10^{6} CFU/mL	
	Listeria monocytogenes	Polyclonal antibody	0.7 X 10^{6} CFU/mL	
	Feline calicivirus (FCV)	Anti-FCV	10^{4} $TCID_{50}$ FCV/mL	Cell culture medium
	Salmonella enteritis	Specific antibodies	23 CFU/mL	Spiked skim Milk
	E.coli	Specific antibodies	25 CFU/mL	Spiked skimmed milk
	Listeria monocytogenes	Anti-fab antibody	10^{5} cells/mL	Buffer solution
	Salmonella group B,D and E	Specific antibodies	170 CFU/µL	Cell culture medium
	E.coli O157:H7	Specific antibody	3.0 X10^{4} CFU/mL	Cell culture medium
Spreeta	Salmonella enteritis	Specific antibodies	10^{5} CFU/mL	Chicken Brest
	Salmonella thyphimurium	Specific anti bodies	10^{6}	Chicken carcass

	Entamobea histolytica	SPCE	10 pg/mL	Stool
	Legionella pneumophila	Ag-SPC	50 p.m.	Environmental sample
	BS2 bacteriophage	CNT/Au	9.3 pfu/mL	Wastewater
	Listeria monocytogenes	-	1000 CFU /mL	Spiked lettuce
	Aeromonas hydrophila	DNA probe /MWCNT	10^{-13} M	Fish, vegetable
	Adenovirus	IgG/PANI/2-ABA	1000 virus particles/mL	-
GAMRY Instruments	P.aeruginosa	rGO-HBC nanocomposite	OD_{600}=.025	-
	E.coli	PAA/PVA-NF-LAPS	20 CFU/ mL	Water
	Papaya ringspot virus	Antibody-PDMS	0.01 ng/mL	Plant extracts
	Streptomyces spp.	MWCNT	-	Culture medium
	Candida albicans	CPE	3X 10^5 – 1.6 X 10^7 cells/mL	Culture medium
PalmSens	E.coli	T7-bacteriophage	100 CFU/mL	Water, apple juice milk
	E.coli	SPCE	70 CFU/mL	Culture medium
	E.coli	Au	250/mL	-
	Pseudomonas fluorescens	Chitosan/graphite/CN	-	-
	Mycobacterium tuberculosis	SPCE	-	-
	Aspergillus	CPE	0.25µg/mL DNA	Culture medium
	Hepatitis A virus	SPCE	10^{-12} IU/mL	Water
	Salmonella	ELIME	1-10 CFU/ 25 g	Irrigation water
	Penicillium chrysogenum	Au micro electrode	600 CFU/ mL	Cultute medium

Gaps

- Better nationwide policies on biological disasters and improvement in public health infrastructure.
- Introduction of mandatory certification and validation mechanisms for biosafety level-2 (BSL-2) labs that sometimes work with high-risk pathogen (Sharma, 2020)
- For pathogen detection, PCR method dominates the practice, but it requires sample preparation to extract DNA or RNA, and its performance heavily depends on reagent quality (DNA primers and enzymes etc.) and PCR apparatus.
- The uncontrollable environmental factor may pose challenges to the reliability of the sensing technologies.
- Wider compatibility of the sensors in seawater and unstable chemical composition (Su, 2020)

ANNEX III- AIR

Indigenous R&D in air quality sensors

Nitrogen Dioxide (NO_2)

The FET sensor adopted a charge trapping mechanism to measure the NO_2 in ambient conditions. The dynamic range measured was from 1 ppb to 103 ppb with a LOD of 40 ppb. The sensor was validated with calibrated reference sensor (Andringa, 2014). Pd-AlGaN/GaN high electron mobility transistors (HEMTs) showed a sensitivity of 91.6 % and a response time of 9 s at 300 °C at 100 ppm NO_2 concentration (Nguyen, 2021). A Si back gate with a tunable C-AlGaN gate dielectric is used as a tunable parameter for improving the selectivity of NO_2 (60% increase without gate bias) and SO_2 (10%) sensing at room temperature. Al_2O_3 passivated and non-passivated MoS_2 thin-film transistors (TFTs) are investigated for NO_2 detection, and a maximum sensitivity of ~6 and ∼18 at 500 ppm is observed for the sensors(Im, 2019). Capacitive-type FET (CFET) gas sensor based on Si MOSFET was used for the detection of 0.25 ppm to 2.5 ppm NO_2 with a recovery time of 417s and 39.2 % for 2.5 ppm(Hong, 2020). An indium-gallium-zinc oxide (IGZO) thin-film transistor (TFT) was used for the detection of NO_2 gas(Park, 2019). Flexible organic thin-film transistor gas sensors with polymethyl methacrylate (PMMA) as gate dielectric layer and poly(3-hexylthiophene) (P3HT)/graphene composite materials as the active layer was used for the detection from 10 ppm to 80 ppm NO_2 with a sensitivity of 0.086(Xie, 2018). Active-matrix gas sensor arrays show a good response from 1 to 256 ppm of NO_2 gas(Kim, 2020). Chemical vapour deposition of graphene has shown a sensitivity of 100 ppb for NO_2. The gas adsorption is reversible and can be removed by heating the film(Yavari, 2012a). The other methods using graphene sheets are capable of detection in the ppm range with hydrazine-reduced graphene oxide sheets having a LOD of 5 ppm, thermally reduced graphene oxide 2 ppm, graphene foam 3 with 20 ppm, and epitaxially grown graphene with a detection limit of 2.5 ppm of NO_2 in the air. Graphene hybridised with AuNPs showed a fast response time of 135s, 3.2 % for 50 ppm NO_2 gas and recovery time of 136s(Rattan, 2022). Graphene decorated with monodispersed polymer beads has shown a marked improvement in NO_2 detection of 0.5 ppb due to the surface plasmon polaritons getting excited by interference resulting in the transfer of charge between the polymer beads(Fei, 2019). A ZnO/rGO complex sensor exhibits a wide range of NO_2 sensing responses from 5 ppb to 10 ppm with a response time of 13.46s when exposed to 2 ppm NO_2 at room temperature(Chen, 2021). Tungsten trioxide (WO_3) decorated nitrogen-doped graphene (N-GO) sheets can detect NO_2 or CO based on a variation of N-GO concentration. A response time of 90 s and recovery time of 205s was achieved for WO_3–N-GO 6% 200 ppm (Badiezadeh, 2021).

SWCNTs decorated with Pt NPs showed enhanced sensitivity and specificity. The LOD was 2 ppm with the enhancement of ~5 than the pure SWCNT with a dynamic range of 2 ppm to 5 ppm(Choi, 2017). ZnO NP coating on SWCNT gave a recoverable NO_2 sensor and measured concentrations upto 1000 ppm at 150 ºC (Barthwal, 2018). SWCNTs decorated with TiO_2 and AuNPs were used for the detection of NO_2 using pulsed temperature mode from 12 ppm to 40 ppm at 50 % power saving pulsed temperature measurement profile grants a power-saving of approximately 50 % for the constant temperature measurement profile with 5 min recovery time and 2 min response time at 25 ppm NO_2 for SWCNT-TiO_2; 6 min recovery time and 2 min response time 25 ppm NO_2 for SWCNT-Au (Panzardi, 2020). DWNTs and MWNTs sensor gave a low sensing concentration of 0.1 ppm with high specificity at temperature ranges between 100 and 200 °C (Sayago, 2008). A 3D SiO_2 MWCNT NO_2 gas sensor was fabricated with a sensitivity of 82.61 % towards 1 ppm NO_2 and a recovery time of ~44s (Ma, 2020). A CNT/SnO_2 composite gas sensor for NO_2 detection was fabricated, and the sensor response to 10 ppb, 50 ppb, 100 ppb and 1 ppm NO_2 concentrations were measured. The response time was faster for 1 ppm than 10 ppb (Phansiri, 2020). NP deposition on a polymer substrate has shown an excellent response to NO_2 sensing. Aligned In_2O_3 nanowires on the polyimide substrate have resulted in a detection limit of 10 ppb at room temperature for visible light excitation(Wang, 2020). Carboxyl modified cobalt phthalocyanine (CoPc) polymer has demonstrated a LOD of 50 ppb and a good recovery time at room temperature and laser exposure at 50 ppm NO_2(Jiang, 2020).

Ammonia

An organic FET (OFET) based NH_3 gas sensors were fabricated by incorporating a simple solution-processed hybrid dielectric, which consists of poly(methyl methacrylate) (PMMA) and graphene Oxide. Compared with those with pure PMMA dielectric, the sensitivity of OFET sensors with hybrid dielectric had two orders of magnitude enhancement from 1.4 % to 30 %(Fan, 2019). An ultrathin 3 nm nanowire FET(NW FET) based NH_3 gas sensor is designed, and its sensitivity is analysed at room temperature. The gas-sensing performance analysis has been done for three different catalysts, iridium (Ir), ruthenium (Ru), and palladium (Pd), with the best result for Pd metal with an increase of sensing response by 90.2 %(Verma, 2021). OFET fabricated in bottom-gate bottom-contact configuration using the organic semiconductor [2,5-(2-octyl dodecyl)-3,6-diketopyrrolopyrrole-alt-5,5-(2,5-di(thien-2-yl)thieno] [3,2-b]thiophene) (DPP-T-TT) with a sensitivity of 2.17 ppb (Mougkogiannis, 2021). SiC-FET-type gas sensors and SiC-capacitor type gas sensors with a gate stack including YSZ, nickel oxide and Pt were developed to detect NO, O_2, NH_3, CO, and SO_2(Y. Sasago, 2020).

The detection limits of ~500 ppb for NH_3 using SWCNT was detected(Yavari, 2012b). A 3D network of graphene sheets (graphene foam3) was also used to detect 20 ppm of NH_3 and NO_2 in air(Guo, 2018). Reduced holey graphene oxide (rHGO) thin-film NH_3

sensors showed a resistance of 2.81 % at 1 ppm and a resistance change of 11.32 % at 50 ppm with good repeatability and recovery time (2 min) (Yang, 2019). SWCNTs, pristine SWCNTs, B-doped SWCNTs, and N-doped SWCNTs exhibited a measurable response to 1.5, 2.5, 5, and 20 ppm of NH_3, respectively semiconductor based-SWCNTs exhibited at 100 ppb after a few minutes of exposure with a low power consumption of 0.6 µW. The semiconductor-based SWCNT is compact and works at room temperature (Panes-Ruiz, 2018).

rGO–polyaniline (PANI) hybrids were used to detect NH_3 with a better response of 3.4 and 10.4 times, respectively, at 50 ppm than those of the bare PANI nanofibre sensor and bare graphene device. The sensor has detection from 5-500 ppm with 4 min response time at room conditions (Huang, 2012). rGO-doped poly (3, 4-ethylene dioxythiophene)-poly (styrene sulfonate) (PEDOT-PSS) organic thin film has been used for the detection of NH_3 gas at room temperature with 200-1000 ppm with 1.05 response time (Pasha, 2019). The lowest NH_3 detection limit found in literature is 1 ppm, using a WO_3 NH_3 sensor with Au and MoO_3 additives. The sensor is operated at an elevated temperature of more than 400 °C(Xu, 2000). Systems with a detection limit of 1 ppb that do a complete measurement in 1 s have been reported (Mount, 2002).

Hydrogen Sulfide (H_2S)

The effect of IGZO film thickness on the H_2S gas sensing performance in the resistor- and FET-type gas sensors was studied, and a 60 nm thick film gave the best response(Shin, 2021). The catalytic effects of Au and Pt NP layer deposition on highly sensitive ZnO nanowires (NWs) was used for selective H_2S detection in the sub-ppm region(Kaiser, 2020). Two concentrations of H_2S (40 and 100 ppm) was detected using two different polymers, polypyrrole polymer and copper oxide–tin oxide/polypyrrole(Elshenety, 2019). H_2S selective ChemFET devices based on a nitrile butadiene rubber membrane containing tetraoctylammonium nitrate as a chemical recognition element is applied to commercially available FETs. The sensors have fast (120 s) reversible responses, selectivity over other biologically relevant thiol-containing species, detection limits of 8 mM, and a detection range from approximately 5 to 500 mM (Sherbow, 2021).

The CNTs/SnO_2/CuO sensor was used to measure H_2S with a response and recovery time of 4 min, and 10 min, respectively and the value of sensitivity is 4.41. Meanwhile, the CNTs/SnO_2/CuO sensor also has a low detection limit, high selectivity toward H_2S, and stable performance with different concentrations of H_2S (Zhao, 2020). A chemiresistive sensor device that applies a composite of SWCNTs and brominated fullerene ($C_{60}Br_{24}$) as a sensing component is capable of detecting 50 ppb H_2S even at room temperature with an excellent response of 1.75 % in a selective manner(Zhou, 2021a). SWCNT and an ion-in-conjugation polymer, poly(1,5- diaminonaphthalene-

squaraine), capable of detecting H_2S and NH_3 in the air even at room temperature with a theoretical concentration limit of ~1 ppb and ~7 ppb(Zhou, 2021b). Hybrid composites based on tin chloride and the conductive polymers, polyaniline (PAni) and poly(3,4-ethylene dioxythiophene) polystyrene sulfonate (PEDOT: PSS) were integrated into high-performance H_2S gas sensors working at room temperature.
The hybrid sensors exhibited a very low detection limit (<85 ppb), fast response, repeatability, reproducibility and stability over one month (Duc, 2021). Polyaniline nanofibre based thin films on silicon substrate gave the best sensitivity of 7.32 % at a working temperature of 150 °C, along with fast response time and recovery time (Akber, 2020).

Ultrathin Au film electrodes (UTGFE) were produced by physical vapour deposition of Au on nanostructured latex-coated paper substrate. The gas-sensing film was deposited on the electrodes by inkjet printing to be used for qualitative and quantitative detection (as low as 1.5 ppm) of H_2S gas(Sarfraz, 2019). It is shown that chitosan/Ag and chitosan/Au based sensors allow detection of H_2S gas at concentration ranges 0.1–100 ppm and 5–300 ppm correspondently(Mironenko, 2016). Here, we report the incorporation of rGO on β-Ga_2O_3 (β-Ga_2O_3/rGO) sensing layers followed by its deposition on alumina substrate by drop-casting method for H_2S gas sensing application. The gas sensing results revealed superior sensitivity and selectivity of β-Ga_2O_3/rGO towards H_2S detection when compared with different interfering gases (NH_3, SO_2, CO_2 and CO) (Balasubramani, 2020).

Carbon monoxide (CO)

The design, fabrication, and characterisation of a middle-infrared (MIR) linear variable optical filter (LVOF) and thermopile detectors that will be used in a miniaturised mixed gas detector for CH_4/CO_2/CO measurement (Zhang, 2019b). A highly sensitive and efficient SPR gas sensor (prism/Au/ZnO) has been fabricated for CO gas detection using ZnO sensing layer. The optimised ZnO thin film of 200 nm thick and grown at 250 °C substrate temperature exhibits an enhanced and stable sensing response towards CO gas over the wide concentration range (0.5–100 ppm). The developed sensor shows a quick response (1 s) and high sensitivity (0.091°/ppm) towards CO gas (Paliwal, 2017). An Au/Nd_2O_3–$Ca_3Nd_2O_6$ composite based on chemiluminescence at a temperature lower than 200 °C with a detection limit (3σ) is 0.2 mg/m^3 (Zhang, 2020). SnO_2 MEMS-based thin-film CO sensor was used to detect Co with a sensitivity of 59 % at a temperature of 270°C (Lee, 2010). Cu-SnO_2 thin film CO sensor was used to detect CO with a fast response time of 5-10 s (Sharma, 2001). Pd-ZnO has a CO detection response and recovery time of 25 s and 12 s respectively (Wei, 2010). Single-Chip four elements gas sensor array device structure for monitoring air pollutants, namely CO, CO_2, NO_2, and SO_2, was simulated, fabricated, packaged and tested. The four micro-heaters share a single suspended SiO_2 diaphragm, utilising thermal proximity to achieve low power consumption (~10mW for 300°C) and maximum repeatable response to CO (~ 78.3 % for 4.75 ppm), CO_2 (~ 65 % for 900 ppm), NO_2 (~ 1948.8 % for 0.9 ppm) and SO_2 (~ 77% for 3 ppm) at operating temperatures of 330°C, 298°C, 150°C and 405°C, respectively.

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Bio Nano Consulting, a division of AquAffirm Ltd is a London-based technology consultancy providing international project management, product development and innovation consulting. Bio Nano Consulting has a deep expertise in sensor development and work on product development commercializing technologies to address environmental issues, the team is ideally placed to provide consultancy for a broad range of technologies. Dr. David Sarphie, Dr. Salzitsa Anastasova (MRSC, FHEA) and Marta Jesus Cintra from AquAffirm contributed to this report.

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Landscaping Review for the UK & India

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