Water Research 261 (2024) 122028

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Review

Plastic pollution and human pathogens: Towards a conceptual shift in risk management at bathing water and beach environments

David M. Oliver [a,*], Rebecca Metcalf [a], Davey L. Jones [b], Sabine Matallana-Surget [a], David N. Thomas [c], Peter Robins [d], Constance L. Tulloch [b], Benjamin M. Cotterell [b], Gwion Williams [b], Joseph A. Christie-Oleza [e], Richard S. Quilliam [a]

[a] Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling FK9 4LA, UK
[b] School of Environmental and Natural Sciences, Bangor University, Bangor, Gwynedd LL57 2UW, UK
[c] Faculty of Biological & Environmental Sciences, University of Helsinki, PO Box 65 (Viikinkaari 1), Helsinki FI-00014, Finland
[d] School of Ocean Sciences, Bangor University, Marine Centre Wales, Menai Bridge LL59 5AB, UK
[e] Department of Biology, University of the Balearic Islands, Palma 07122, Spain

ARTICLE INFO

Keywords:
Biofilm
Microplastics
Plastisphere
Public health risk
Sewage-related debris

ABSTRACT

Emerging evidence indicates that micro- and macro-plastics present in water can support a diverse microbial community, including potential human pathogens (e.g., bacteria, viruses). This interaction raises important concerns surrounding the role and suitability of current bathing water regulations and associated pathogen exposure risk within beach environments. In response to this, we critically evaluated the available evidence on plastic-pathogen interactions and identified major gaps in knowledge. This review highlighted the need for a conceptual shift in risk management at public beaches recognising: (i) interconnected environmental risks, e.g., associations between microbial compliance parameters, potential pathogens and both contemporary and legacy plastic pollution; and (ii) an appreciation of risk of exposure to plastic co-pollutants for both water and waterside users. We present a decision-making framework to identify options to manage plastic-associated pathogen risks alongside short- and longer-term research priorities. This advance will help deliver improvements in managing plastic-associated pathogen risk, acknowledging that human exposure potential is not limited to only those who engage in water-based activity. We argue that adopting these recommendations will help create an integrated approach to managing and reducing human exposure to pathogens at bathing, recreational water and beach environments.

1. Introduction

Environmental legislation and associated regulation evolve over time to reflect new scientific understanding and evidence. Evidence-based policy, therefore, provides underpinning support for the protection of environmental quality and public health (Sánchez-García et al., 2023; Holmes and Clark, 2008). For example, the EU Bathing Waters Directive (BWD) (2006) provides the regulatory basis for managing risks to human health from faecal pollution at designated coastal, lacustrine and riverine bathing waters. The BWD has evolved since its introduction in 1976, with regulations revoked and replaced over time to continue its implementation (Kay et al., 2004; Oliver et al., 2014). Currently the BWD and similar non-EU legislation, e.g., US Recreational Water Quality Criteria (RWQC), focus on microbial quality of the aquatic environment, whether marine or freshwater, and consider the potential risk to only those who engage in water-based activity. However, new data show that other pollutants (e.g., micro- and macro-plastics) are rapidly colonised by microbial communities. This colonisation can facilitate the association of potentially infectious viral (e.g., rotavirus), bacterial (e.g., *Salmonella* spp, *E. coli*) and fungal (e.g., *Candida* spp.) pathogens with plastic surfaces (Moresco et al., 2022; Witsø et al., 2023; Metcalf et al., 2024a, Vass et al., 2024), which may remain viable during their transfer through the riverine-estuarine-marine-beach continuum as plastic co-pollutants (Metcalf et al., 2023).

The interaction between plastic and microbial pollution, and in particular potential human pathogens, raises important questions concerning the role and suitability of current bathing and recreational water regulation and associated risks at beach environments around the world.

---

* Corresponding author.
E-mail address: david.oliver@stir.ac.uk (D.M. Oliver).

https://doi.org/10.1016/j.watres.2024.122028
Received 30 April 2024; Received in revised form 27 June 2024; Accepted 30 June 2024

Furthermore, the increase in plastic debris (from both sewage and non-sewage sources) on shorelines highlights the potential for human contact with microbial hazards without any direct engagement with the water environment (Metcalf et al., 2024b; Magalhães et al., 2024). Risk of acquiring infection from recreational exposure to seawater has been demonstrated (Leonard et al., 2018); however, in response to this significant potential public health issue, we propose the need for a conceptual shift in risk management at public beaches to recognise: (i) interconnected environmental risks, e.g., associations between microbial compliance parameters, potential pathogens and both contemporary and legacy plastic pollution; and (ii) an appreciation of risks to both water and waterside users. Here we outline the evidence in support of this conceptual shift in thinking and propose a series of priority requirements that would help to underpin a transition to more effective management of microbiological risks associated with plastic pollution at bathing waters and public beaches.

2. Bathing water quality and the 'hidden majority' of beach users

In coastal locations, healthy bathing/recreational waters represent a diverse and valuable component of the marine system. They integrate nearshore and beach environments to provide social spaces, health-promoting and wellbeing opportunities for recreational users, and revenue to support local economies (Grace et al., 2023). Bathing waters also provide amenity value beyond recreational pursuits linked to bathing, including social, aesthetic, cultural and wider wellbeing benefits that individuals associate with sand dune, beach and nearshore zones (Garrett et al., 2023). Improvements in bathing and recreational water quality have provided safer environments for bathers; however, the 'hidden majority' of beach users do not engage in sea swimming and therefore do not benefit directly from water quality monitoring (Elliott et al., 2018; Coombes and Jones, 2010).

Appreciating the wider set of values that people attribute to bathing water access, distributed across a broad range of users, is important to promote inclusivity and support better beach management for those who engage in different recreational pursuits afforded by bathing water environments (Pascoe, 2019). For example, direct contact with beach sand can facilitate potential exposure to pathogens (Halliday and Gast, 2011; Whitman et al., 2014; Solo-Gabriele et al., 2016). In addition, plastic pollution on beaches provides further opportunities for beach-users to encounter pathogens given their potential to associate with biofilm on plastic surfaces (Rodrigues et al., 2019). This includes exposure to faecal indicator organisms (FIOs, e.g., *E. coli* and intestinal enterococci) and potential pathogens associated with sewage-related plastic debris (Metcalf et al., 2022a; Ormsby et al., 2023), but also plastic material that has been delivered into the environment through a variety of other sources, e.g., fishing (Wright et al., 2021), shipping (Saliba et al., 2022), other beach-users (Watts et al, 2017), agriculture (Cusworth et al., 2024; Li et al., 2022), urban runoff (Müller et al., 2020), all of which may be (re)colonised by FIOs and pathogens over time.

For parity, beach users should also benefit from a degree of protection from the same hazards that are being monitored in the water environment for bathers, or at least have access to information at the beach that raises their awareness of potential risk to their health. How that would be implemented by regulators or beach managers in terms of risk management is uncertain, but mounting evidence highlights a wider range of exposure pathways for direct human contact with potentially harmful microorganisms at beach environments beyond those associated with ingestion of contaminated water during swimming (Metcalf et al., 2023; Metcalf et al, 2022a; Moresco et al, 2021).

3. Opportunities for pathogen colonisation of plastic

The presence of plastics in the environment can signal an escape from a waste management cycle (Zeb et al., 2023), represent the breakdown and eroding of plastic from a point-of-use in the environment (Bodor et al., 2024), or reflect accidental or intentional environmental littering ranging from personal to industrial scales (Gül, 2023; Saliba et al., 2022). Upon entering the environment, plastic surfaces can be rapidly colonised by microbial biofilm, resulting in a so-called 'plastisphere' community (Zettler et al., 2013). For sewage-associated plastic debris this colonisation starts during passage through the sewer network and wastewater treatment works (WWTW). If plastic-environment interactions include exposure to faecal material, e.g., from raw sewage or faecally-contaminated land and water matrices, there will be potential for human pathogens to associate with the plastisphere. There is also evidence that biofilm on micro- and macro-plastic can function as a reservoir of antimicrobial resistance genes (ARGs), demonstrating a further public health risk associated with the plastisphere (Luo et al., 2023, Silva et al., 2023; Zadjelovic et al., 2023; Müller et al., 2024).

3.1. Combined sewer overflows: spilling the dirt (and plastic)

The close contact of plastics with microorganisms within sewerage infrastructure and WWTW provides ample opportunities for microbial colonisation of plastic surfaces through the formation of biofilms (Liu et al., 2023). Thus, when a combined sewer overflow (CSO) discharges, it could release plastic material that is harbouring microorganisms of regulatory or potentially human health concern, directly into the riverine-estuarine-coastal environment, bypassing several stages of wastewater treatment within the WWTW (Giakoumis and Voulvoulis, 2023). To date, much of the debate concerning CSOs has focused on the immediate impacts of sewage spills to the hygienic status of the receiving water and downstream impacts on coastal water quality, in particular at bathing beaches, as inferred through the use of the microbial compliance parameters, e.g., *E. coli* and intestinal enterococci (Zan et al., 2023; Locatelli et al., 2020). However, a secondary issue is the delivery of plastic (spanning nano, micro and macro scales) via both treated and untreated wastewater discharge to receiving waters (microplastic discharges of 2.2×10^7 particles day^{-1} have been reported from a WWTW with tertiary level treatment under low to medium flow conditions) (Blair et al., 2019). Untreated discharge can also export larger macroplastics, including inappropriately flushed plastic-laden sanitary products and wet wipes, if the CSO screening is bypassed.

Consequently, there is potential for legacy stores of FIOs, pathogens, ARGs, and plastic particles and fragments to accumulate over time in riverbed sediments near to where CSOs discharge, providing further opportunities for pollutant interactions and pathogen (re)colonisation of plastic. These legacy stores, or hotspots, in riverbed sediments are likely to be dynamic, varying in size distribution and locations through a net effect of input factors (e.g., sedimentation as a function of flow rate, shear velocity and turbulence) and removal processes (e.g., resuspension mechanisms that erode the riverbed supplies and promote subsequent dissemination and transport due to properties of plastic) (Kroeze et al., 2016). The presence of legacy stores of microbial and plastic pollutants in riverbed sediments could therefore provide a potential in-stream source of contamination, resulting in delayed impairment of water quality in riverine/estuarine and downstream coastal bathing water zones following eventual resuspension into the water column (Afolabi et al., 2023; Nyberg et al., 2023).

Legislation and permits define the sewer volume above which a CSO can legally spill. Under higher flows, faecal solids will be diluted and associated microorganisms may dissipate more rapidly and decline through dispersal and die-off processes to concentrations below thresholds used as regulatory standards; however, plastics (whether fibres, nano, micro, fragments or macro) will behave differently and persist much longer, breaking down into smaller (secondary) plastic particles that will represent significant problems in the future, with respect to both the plastic itself but also their co-pollutants (Monira et al., 2023). Buoyancy, durability and the diversity of plastic types and sizes therefore contribute a very different environmental management challenge relative to the microbiological load of a CSO spill. When a storm hydrograph subsides, larger plastics discharged from a CSO will likely end up trapped in riverside vegetation or in shoreline debris, along with their co-pollutants (Perry et al., 2024).

3.2. *Plastic-pathogen associations in the wider environment*

Pathogen associations with plastic particles can be facilitated within a range of other environmental settings. For example, interactions between microplastics and pathogens can occur within aquatic systems such as aquaculture facilities (Zhong et al., 2023). Terrestrial ecosystems also represent a significant sink for plastics, receiving inputs from landfill or, if waste management options are limited, via direct dumping in the environment allowing for plastics to mix with faecal material from vermin, wildlife or diaper waste (White et al., 2023; Zhang et al., 2024). In areas with poor sanitation, plastic waste may be dumped in rivers alongside untreated human- and animal-derived sewage. In agroecosystems, microplastics arise from soil amendments such as compost and sewage sludge (Bodor et al., 2024) and the use of agriplastics such as plastic mulching, plastic piping, seed and fertiliser coatings (Qi et al., 2020; Shafea et al., 2023) in addition to irrigation water containing microplastics (Jiang et al., 2023). Residues in soil from plastic films can be exposed to cultivation practices and will also undergo mechanical abrasion, fragmenting into increasingly smaller particles (He et al., 2018). In agricultural systems the mixing of faeces, manures, slurries and on-farm plastics provides potential opportunities for faecal microbes to interact with plastic surfaces (Quilliam et al., 2023). Agricultural land can therefore act as a source of microbially contaminated microplastic to the wider environment, delivering plastic fragments and their co-pollutants from land to water via agricultural runoff; however, the contribution from this terrestrial source is less well studied relative to WWTW (Schell et al., 2022). Microplastics derived from tyre abrasion may also be readily lost to aquatic environments via road runoff (Mayer et al., 2024).

Large quantities of plastic debris are already present in the environment. Oceanic plastic debris arising from shipping and fishing industries and from general plastic litter, having escaped waste management cycles, provide surfaces for biofilm formation and pathogen (re)colonisation and represent a significant source of plastic that has been accumulating for decades (Magalhães et al., 2024). Furthermore, plastic debris in the environment will undergo environmental weathering and physical and chemical erosion, increasing surface area availability for biofilm colonisation and association of pathogens (Zhong et al., 2023; Shafi et al., 2024).

Inland and coastal CSO discharges provide a relatively direct (and local) hydrological connection to beach environments for plastics and their co-pollutants via the catchment drainage network. The timing of delivery to the coastal zone is influenced by proximity of the CSO but also river and estuary characteristics and how different plastic fragments are impacted by flow dynamics (Jago et al., 2024). However, the wide range of potentially much more distant sources of micro- and macro-plastics, and their indirect points of entry to the nearshore zone, underscores the complexity of understanding (re)colonisation dynamics of pathogens on plastic surfaces and challenges for managing risks at bathing waters and beaches. Crucially, there also remains considerable uncertainty regarding whether plastics are more readily colonised by biofilm (and potential pathogens) relative to other natural debris, and whether pathogens colonising the plastisphere are likely to pose any more of a risk, with contradictory views and differences noted depending on environmental context (Beans, 2023; Beloe et al., 2022; Metcalf et al., 2022b). For example, the majority of plastisphere studies have focused on microbial colonisation of plastic and determining the presence/absence of microorganisms, with subsequent survival and transfer processes often assumed rather than demonstrated (Beloe et al., 2022). Inconsistent evidence of preferential pathogen colonisation on plastics relative to other materials in the environment suggests that environmental factors rather than polymer type are more important in influencing plastisphere formation (Metcalf et al., 2022b). Despite this, how colonisation, survival, and transfer are influenced over multiple seasons or sites and how this ultimately impacts on risk to human health are rarely reported (Beloe et al., 2022). Furthermore, disease potential requires a quantification of the associated microorganisms of concern, which is often lacking. To some extent this has been caused by the reliance on detection of pathogens by qPCR and genomic approaches that provide no information on their viability and potential human infection risk (Kevill et al., 2023).

4. Recommendations to support a conceptual shift in risk management at bathing beaches

Plastic-associated pathogens are found in bathing waters and beach environments but have yet to be formally recognised as a threat to human health, e.g., via the BWD or revised strategies to risk management at the beach. Undoubtedly, this requires investment of both time and resource, which is challenging when funding available to support environmental regulation is limited. Irrespective of what measures and proposals are achievable in different regions of the world, it is appropriate and timely to reflect on scenarios for managing exposure pathways of pathogens associated with plastic and sewage-related debris. Here we provide a series of recommendations that would help to deliver a conceptual shift in risk management at bathing beaches; one that recognises the co-pollutant potential of plastic debris, and that human exposure potential is not limited to only those who use the water environment as part of a recreational visit to the beach. Addressing the following priorities would help to pave the way for a more integrated approach to managing human exposure to pathogens at designated bathing waters and beach environments. These recommendations combine to form a roadmap of future priorities and are categorised and outlined below as short (<5yr) and longer-term (5-10yr +) needs.

4.1. *Short term priorities (within 5 years)*

Recommendation 1 (R1) International joint-agency task force on plastisphere-associated risk to human health. Establishing an international, joint-agency task force to help facilitate initial shifts in conceptual understanding of beach-related risks from plastic-associated pathogens is an important first step to bring about coordinated change. This should involve policy makers, regulators, water industry practitioners, campaign groups and research community stakeholders. However, participation in existing bathing and recreational water steering groups at national levels should also be broadened to reflect expertise in plastic pollution, facilitating increased debate on how plastic surfaces colonised with biofilm may influence risk to human health at bathing beaches. Integrating interdisciplinary knowledge on the fate, behaviour and modelling of plastics in the environment with microbiology, public health and environmental management expertise would help to co-create a pathway for implementing any required change in bathing water policy and practice, promote greater action at the science:policy interface and accelerate a shift in focus beyond that of only faecal pollution in bathing waters, particularly if national steering groups formalise an approach to share best practice internationally regarding risks arising from plastisphere communities. Providing timely availability of such information, driven by the formation of an international joint-agency task force, would aid regulators to manage risks to human health from plastic debris (Vethaak and Leslie, 2016). Emerging agendas on integrated ocean and human health have identified similar benefits via the proposal for a joint oceans and human health research and governance programme in Europe (Borja et al., 2020).

Recommendation 2 (R2) Revisions to wastewater regulation and new monitoring guidelines for plastics. Current revisions to the EU urban wastewater treatment directive (UWWTD) and the development of monitoring guidelines for plastic provide options for more effective management of a broader range of risks at bathing waters. Provisional political agreement has been reached on a proposal to review and extend the scope of the UWWTD, driven by a changing climate, changing awareness of risks posed to downstream receptors and aging infrastructure originally built to process much smaller volumes of wastewater (Whelan et al., 2022). Extending the scope of the UWWTD includes the alignment of thresholds and timelines for quaternary treatment (i.e., removal of a suite of micropollutants) in larger WWTW catering for population equivalents of >150,000 and strategic routes for upgrading WWTW (Abily et al., 2023). The provisional agreement also highlights a need for systematic monitoring of microplastics within CSO discharges and the need for a sampling programme to enable microplastic concentration and flux estimation in discharges of urban runoff to assist water quality modelling (European Parliament, 2023). This provides an impetus to drive forward strategies for environmental monitoring of plastic, but specific detail on approaches to plastic pollution monitoring remain vague. Crucially, extending that monitoring to include plastisphere-associated FIOs and potential pathogens would deliver significant added-value and help develop guidelines for wider environmental monitoring of plastic-associated pathogens, which would likely attract interest from environmental departments of national government. This is especially the case for viral, fungal and protozoal pathogens for which no standard methods or risk categories exist. Collaborating with the modelling community would be important to help to establish the right spatial and temporal resolution of monitoring alongside the validation/accreditation of methods (Oliver et al., 2016a). Revisions to the UWWTD should help in the management of contemporary emissions to water of (micro)plastics and their co-pollutants given that WWTW are one of the main sources of plastics to the wider environment; however, there remains a need to consider a wider range of sources, as described earlier.

Recommendation 3 (R3) Plastisphere monitoring as part of bathing and recreational water regulation. Building on *R1* and *R2*, some form of regulatory monitoring of plastic, e.g., as part of the BWD, is also advocated. Effective monitoring of microplastic for associated microbial compliance parameters and/or potential pathogens would be challenging and is realistically a much longer-term ambition due to difficulties associated with sample processing, a lack of standardisation and available range of permutations of plastic size, shape, density and chemical signatures (Phan and Luscombe, 2023; Koelmans et al., 2022). However, regulatory monitoring of macroplastic-associated FIOs (and pathogens) could offer greater feasibility. If undertaken, macroplastic-associated plastisphere monitoring could help to identify (i) regions of high loading potential in the environment and (ii) transport patterns of plastics and hitchhiking microbial communities, with that knowledge then helping to underpin strategies to reduce plastic and co-pollutant delivery to the wider environment from WWTW overflows and other sources. The BWD only monitors for FIOs and therefore, aside from plastics, some form of pathogen surveillance, e.g. pathogenic viruses, would be required too. Importantly, employing the right tools to tackle this question is essential. Relying on taxonomic characterisation, such as 16S sequencing, will not provide a comprehensive understanding of the microbial community dynamics, including which organisms are active, dormant, or dead.

Recommendation 4 (R4) Awareness raising and behaviour change. A greater awareness of risk among beach-users, but also the general public, is essential and long-term effectiveness of reducing exposure to plastic-associated pathogens will rely on changing public behaviour. For example, there is an urgency to raise awareness of the risks posed by wet wipes (and other non-flushable single use plastics), especially given the surge in demand for single-use wipes since the COVID-19 pandemic and their subsequent inappropriate domestic disposal (Allison et al., 2023). Wet wipes vary in composition and while some comprise of cotton, bamboo fibres and other 'biodegradable' materials, most are made up of synthetic polymers that over time fragment into plastic microfibres (Allison et al., 2023). While the flushing of wet wipes and their presence within sewage-related debris is a well-documented challenge (Alda-Vidal et al., 2020), new evidence reporting the magnitude of wet wipes of varying composition accumulating on some designated bathing water beaches, and the levels of associated microbial pollutants that they can harbour, reinforces the need to act on this issue (Metcalf et al., 2022a). Furthermore, decreasing the volume of inappropriately flushed 'non-flushables' is also important for reducing sewer blockages and subsequent CSO spills, highlighting how behavioural nudges designed to promote better wet wipe disposal practices could deliver win-win outcomes. It is far more effective to prevent plastic waste at source than to implement infrastructural interventions to restrict plastic delivery to the wider environment (Borg et al., 2022). Increased media reporting on sewage overflows helps to enhance the visibility of wastewater management and infrastructure among the public, which previously may have been relatively unknown to large proportions of the population (Holmberg and Ideland, 2023). Other approaches could include clearer warnings on wet wipe packaging; Water UK has recently removed their Fine to Flush wet wipe certification to encourage users to appropriately dispose of wet wipes (Water UK, 2023). Although a relatively easy win due to lower economic and resource requirements, promoting this strategy remains a significant challenge, e.g., modifying established behaviour and widespread flushing cultures, which appear to be more prevalent in the UK than in member states of the EU (Alda-Vidal et al., 2020).

Recommendation 5 (R5) Public health education campaigns. Due to the high abundance and associated lightweight properties of plastic products, it is likely that beach-users will encounter plastic on the sand surface or trapped within strandline materials on the shore. Colourful plastic pellets (nurdles) can be found at relatively high concentrations when trapped in strandlines on the beach (Rodrigues et al., 2019), and children may be particularly curious to handle these items without knowledge that they potentially harbour faecal microbes. Coordinated education campaigns on the public health risk of plastic pollution at beaches are therefore required to help inform beach-users (and those involved in beach clean activities) about risks from exposure to plastic waste. The BWD already deploys beach signage to communicate the water quality status of designated bathing waters. Although approaches to environmental risk communication via beach signage can be challenging (Oliver et al., 2016b), adopting wider signage to warn of plastic-associated pathogens on the beach could be a complementary approach to existing BWD classification signage. It would, however, require a careful approach to risk communication to avoid scaremongering. An initial trial of signage at high-risk locations (e.g., high visitor numbers, high likelihood of plastic delivery) would be a valuable first step, recognising geographical variability in plastic volume (and therefore risk) at the national scale, and offering a complementary approach to existing app-based technologies that warn beach-users of recent CSO discharges (Evers and Phoenix, 2022). However, a critical challenge in the spatial targeting of such signage is the need for better understanding of the relative risk associated with biofilm on plastic that has travelled long distances and/or persisted in the environment for a significant period of time, versus plastic recently discharged from local CSOs.

Recommendation 6 (R6) Government support for beach clean activities. A final short-term priority is for greater support and funding for beach clean activities. Community groups and NGOs often take the initiative to run beach clean events, but full-time employment opportunities could become the norm if funding was available via local government support in recognition of the multiple benefits that such activities could deliver, e.g. health, social, environmental and economic (Jorgensen et al., 2021). Current beach clean activities are largely driven by a combination of plastic pollution on beaches being a highly visible issue and being a topic that engages the public (Nelms et al., 2022); however, with increased recognition of the wider potential health risks associated with contaminated plastic there is scope to capitalise further on public support. Harnessing the wealth of experience and knowledge of community beach clean organisations would be important. Likewise developing incentive/reward schemes to promote school and other community group involvement in beach cleans would increase awareness and could also deliver educational impact on the topic of plastic-associated pathogens. Linking certification schemes, such as the Blue Flag Award, to a micro- and macro-plastic criterion have also been advocated (Kutralam-Muniasamy et al., 2022), which would further support investment in beach clean activities for wider socio-economic benefits to coastal communities.

4.2. Longer term priorities (5-10 years +)

Recommendation 7 (R7) New policy on public health risk of plastic co-pollutants at the beach. Policy development and/or modification, and new legislation linked to public health risk of pathogen-associated plastics at beach environments, would require the research community to convincingly answer key questions. Those questions span issues around the fate, transfer, exposure and impacts of plastic-associated pathogens in both the aquatic and terrestrial zones of beach environments (Fig. 1). Our knowledge of the role of plastics in facilitating pathogen fate and transfer in the environment is advancing and is helping to influence change in the management of wastewater discharge, but evidence needs to be evaluated carefully to avoid misinterpretation (Beloe et al., 2022). However, our incomplete understanding of environmental risks from microplastic pollution originating from various sources complicates management decisions (Mehinto et al., 2022). There is still much we are to understand of

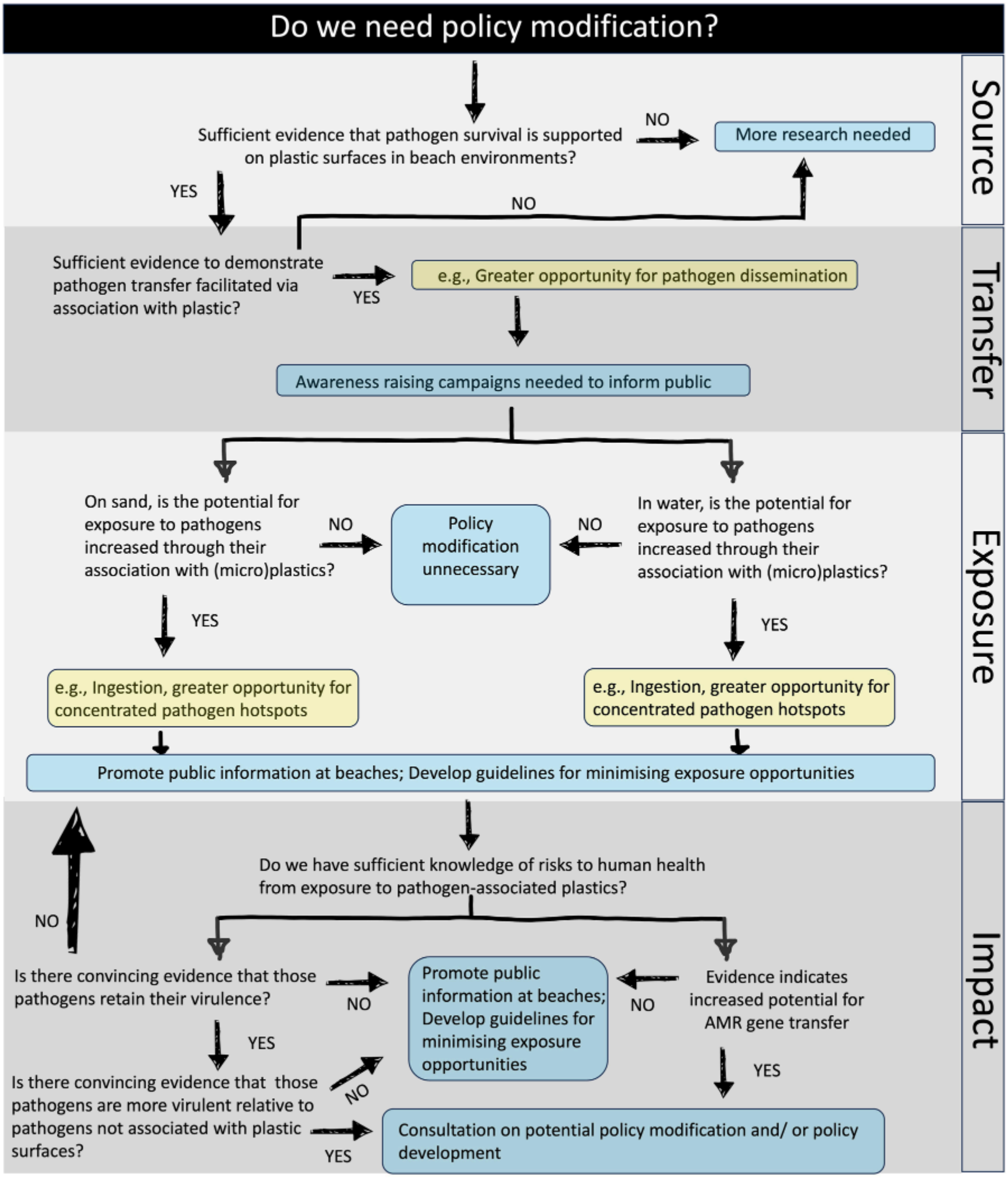

Fig. 1. Decision-making framework for identifying options for managing (micro, macro) plastic-associated pathogen risks relative to current state of evidence.

microbial dynamics of biofilm on plastic debris and the co-pollutant impacts of human exposure to plastics at bathing waters and beach environments before we can conclusively argue for a need for policy change. Consequently, our decision-making framework identifies evidence-appropriate options to manage micro- and macro-plastic-associated pathogen risks (Fig. 1), which should be considered by decision-makers and policy practitioners.

Recommendation 8 (R8) Global legislation. Beyond national policy and piecemeal regulatory measures, global legislation in support of monitoring pathogen risks from beach (and river) plastics would offer significant benefit. Establishing an international, joint-agency task force to conceptualise beach-related risks from plastics and their co-pollutants (*R1)* would be a key precursor to enable this. Critics may argue that globally agreed legislation is overly ambitious or that there remain a series of challenges to overcome due to a lack of harmonised definitions, gaps in understanding, and trade-offs and conflicts between differing policy objectives, among other factors (Kurniawan et al., 2023). Irrespective, the global significance and planetary crisis of plastic pollution led the United Nations Environment Assembly (UNEA) in 2022 to adopt a historic resolution to initiate intergovernmental negotiation and the drafting of a legally binding international treaty on general plastic pollution, although details with respect to the likely content remain vague (Varvastian, 2023). There are many questions and debates regarding this international negotiation (Wang et al., 2023) and reasons for ultimately 'opting in' or 'opting out' will link to legal and political discourse; however, this could represent an important policy instrument within which to also recognise and coordinate the international management of plastic-associated pathogens accumulating at end-point receptors where human exposure is likely, and if omitted, would represent a significant missed opportunity. Further, legacy oceanic plastic, and the potential risks associated with its (re)colonisation by pathogens, needs specific recognition in addition to any global efforts focused on limiting contemporary plastic emissions to the environment (Richon et al., 2023). The international science community should make every effort to amplify the importance of including plastisphere-associated risks within a legally-binding global treaty.

Recommendation 9 (R9) Continued refinement of our modelling capability. Increased investment in our predictive capability of hot spots (spaces) and hot moments (times) for plastic debris and microbial co-pollutants at bathing water environments is recommended. While we can do this already for other targets of interest discharged from WWTPs and CSOs using hydrodynamic models (e.g., Robins et al., 2022), there is a clear need for ongoing refinement so that predictive capability can be captured in real time and includes the behaviour of plastics and their co-pollutants in the environment. To do this effectively requires models to be climate/river flow/tidal driven, which is extremely context specific and in turn requires heavy computation. For sewage-related plastics and their co-pollutants, comprehensive monitoring and the accrual of good quality historical data on WWTW and CSO discharges can provide evidence to underpin model predictions at bathing water beaches, both in terms of aquatic and terrestrial risks. The latter through linking on-the-ground catchment campaigns to track patterns in deposition of sewage related debris following CSO discharges. This type of approach could help to enable spatially targeted (and therefore cost-effective) beach clean activity in the future. However, such an approach does not assist our modelling of non-sewage related plastic or legacy plastic in the environment. Better and longer-term understanding of plastic migration and (re)colonisation drivers is needed to underpin model development and parameterisation when considering micro- and macro-plastics contributed from a wider range of sources beyond WWTW discharge. In addition, hydrodynamic models rely on good quality bathymetric data that is not always available, particularly for near-shore environments. The flocking and deposition behaviour of pathogens and plastics in the river-estuarine transition zone also represents a major source of uncertainty.

Recommendation 10 (R10) Implementing bans. Banning, or increased taxation, of certain types of plastic is an important and actionable recommendation that merits serious consideration as a key step in reducing plastic and potential associated risks. For example, highly recalcitrant single-use C-C backbone plastics (e.g., polyethylene, polypropylene and polystyrene; representing 70 % of global production) are almost impossible to biodegrade in the environment, thus representing a persistent environmental hazard (Ali et al., 2021). Furthermore, the long-lasting buoyant properties of PE and PP allow them to have a much larger dispersal potential than other more dense polymers (Stride et al., 2024), and their entry into the environment therefore provides a surface for (re)colonisation by pathogens for decades to come with implications for large-scale spatial distribution. In September 2023, a ban on the sale of products containing intentionally added microplastics was ratified in the European Union, going further than previous legislation that limited the use of microplastics in personal care products, although such products only account for a relatively small proportion of globally released microplastics (Zuccaro et al., 2024).

Recommendation 11 (R11) Futureproof and cutting-edge engineering solutions. Despite the root cause of the plastic problem being upstream, it is important to recognise that WWTW act as a 'junction box' that link that upstream activity with an opportunity for pathogen colonisation and connection to downstream high value receptors, such as bathing waters and beach environments. Therefore, a final long-term priority is for widespread change in wastewater infrastructure and treatment technology, going beyond typical scenarios of adding incremental processes (Soares, 2020). This would represent futureproofed extension to the UWWTD and link to a pressing need to identify cutting-edge engineering solutions to remove nano- and microplastics from wastewater effluent given that conventional treatment technology was never designed to eliminate these particles (Jose et al., 2024). The elimination of plastic particles in wastewater effluents would simultaneously prevent the delivery of plastic co-pollutants into receiving waters offering win-win opportunities for management of downstream bathing waters and beach environments. Further, more effective removal of plastics at WWTW is also likely to remove pathogens representing a significant co-benefit. It is important to recognise that the scale of plastic pollution (and therefore plastic co-pollutants) will vary between countries and progress in engineering solutions may be more advanced in different geographic regions of the world. The need for sharing of international best practice is therefore implicit within this recommendation. It should be noted that the removal of microplastics into the biosolids fraction may represent a form of pollution swapping if these are subsequently applied to land as an organic fertiliser.

5. Conclusion

Research has shown that plastics can facilitate the persistence and transfer of microorganisms of regulatory and potential health concern. The evidence base to support our understanding of how plastic-associated pathogens affect 'risk' at bathing water and beach environments is more uncertain (e.g., does pathogen association with a plastic surface pose greater risk relative to association with surfaces of natural debris in environmental matrices; and do pathogens colonising plastics retain their virulence and pathogenicity?). Current evidence to underpin full-scale policy modification for addressing the risk posed by plastic-associated pathogens at public beaches is therefore insufficient; however, we propose a series of priority recommendations that, if implemented, would help to support the transition to a new era in risk management at bathing water and beach environments for the benefit of a broader range of beach-users.

CRediT authorship contribution statement

David M. Oliver: Writing – review & editing, Writing – original draft, Conceptualization. **Rebecca Metcalf:** Writing – review & editing. **Davey L. Jones:** Writing – review & editing, Funding acquisition.

Sabine Matallana-Surget: Writing – review & editing. **David N. Thomas:** Writing – review & editing. **Peter Robins:** Writing – review & editing. **Constance L. Tulloch:** Writing – review & editing. **Benjamin M. Cotterell:** Writing – review & editing. **Gwion Williams:** Writing – review & editing. **Joseph A. Christie-Oleza:** Writing – review & editing. **Richard S. Quilliam:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was supported by the UKRI Natural Environment Research Council (NERC) as part of the Plastic Vectors Project, "Microbial hitch-hikers of marine plastics: the survival, persistence & ecology of microbial communities in the 'Plastisphere'" [grant number NE/S005196/1]. This work was also supported by the European Union's Horizon Research and innovation programme under the BlueAdapt project (101057764) and by the UKRI/HM Government.

References

Abily, M., Acuña, V., Corominas, L., Rodríguez-Roda, I., Gernjak, W., 2023. Strategic routes for wastewater treatment plant upgrades to reduce micropollutants in European surface water bodies. J. Clean. Prod. 415, 137867.

Afolabi, E.O., Quilliam, R.S., Oliver, DM., 2023. Persistence of *E. coli* in streambed sediment contaminated with faeces of dairy cows, geese, and deer: legacy risks to environment and health. Int. J. Environ. Res. Public Health 20, 5375.

Alda-Vidal, C., Browne, A.L., Hoolohan, C., 2020. Unflushables": Establishing a global agenda for action on everyday practices associated with sewer blockages, water quality, and plastic pollution. Wiley Interdiscip. Rev. Water 7 (4), e1452.

Ali, S.S., Elsamahy, T., Al-Tohamy, R., Zhu, D., Mahmoud, Y.A.G., Koutra, E., Metwally, M.A., Kornaros, M., Sun, J., 2021. Plastic wastes biodegradation: Mechanisms, challenges and future prospects. Sci. Total Environ. 780, 146590.

Allison, T., Ward, B.D., Harbottle, M., Durance, I., 2023. Do flushed biodegradable wet wipes really degrade? Sci. Total Environ., 164912

Beans, C., 2023. Are microplastics spreading infectious disease? Proc. Natl. Acad. Sci. 120 (31), e2311253120.

Beloe, C.J., Browne, M.A., Johnston, E.L., 2022. Plastic debris as a vector for bacterial disease: an interdisciplinary systematic review. Environ. Sci. Technol. 56 (5), 2950–2958. https://doi.org/10.1021/acs.est.1c05405.

Blair, R.M., Waldron, S., Gauchotte-Lindsay, C., 2019. Average daily flow of microplastics through a tertiary wastewater treatment plant over a ten-month period. Water Res. 163, 114909.

Bodor, A., Feigl, G., Kolossa, B., Mészáros, E., Laczi, K., Kovács, E., Perei, K., Rákhely, G., 2024. Soils in distress: The impacts and ecological risks of (micro) plastic pollution in the terrestrial environment. Ecotoxicol. Environ. Saf. 269, 115807.

Borg, K., Lennox, A., Kaufman, S., Tull, F., Prime, R., Rogers, L., Dunstan, E., 2022. Curbing plastic consumption: A review of single-use plastic behaviour change interventions. J. Clean. Prod. 344, 131077.

Borja, A., White, M.P., Berdalet, E., Bock, N., Eatock, C., Kristensen, P., Leonard, A., Lloret, J., Pahl, S., Parga, M., Prieto, J.V., 2020. Moving toward an agenda on ocean health and human health in Europe. Front. Mar. Sci. 7, 37.

Coombes, E.G., Jones, A.P., 2010. Assessing the impact of climate change on visitor behaviour and habitat use at the coast: A UK case study. Glob. Environ. Change 20 (2), 303–313.

Cusworth, S.J., Davies, W.J., McAinsh, M.R., Gregory, A.S., Storkey, J., Stevens, C.J., 2024. Agricultural fertilisers contribute substantially to microplastic concentrations in UK soils. Commun. Earth Environ. 5 (1), 7.

Elliott, L.R., White, M.P., Grellier, J., Rees, S.E., Waters, R.D., Fleming, L.E., 2018. Recreational visits to marine and coastal environments in England: Where, what, who, why, and when? Mar. Policy 97, 305–314.

European Parliament. 2023. Urban wastewater treatment: updating EU rules. European parliamentary research service briefing paper. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/739370/EPRS_BRI(2023)739370_EN.pdf Accessed 13/03/24.

Evers, C., Phoenix, C., 2022. Relationships between recreation and pollution when striving for wellbeing in blue spaces. Int. J. Environ. Res. Public Health 19 (7), 4170.

Garrett, J.K., White, M.P., Elliott, L.R., Grellier, J., Bell, S., Bratman, G.N., Economou, T., Gascon, M., Lõhmus, M., Nieuwenhuijsen, M., Ojala, A., 2023. Applying an ecosystem services framework on nature and mental health to recreational blue space visits across 18 countries. Sci. Rep. 13 (1), 2209.

Giakoumis, T., Voulvoulis, N., 2023. Combined sewer overflows: relating event duration monitoring data to wastewater systems' capacity in England. Environ. Sci. Water Res. Technol. 9 (3), 707–722.

Grace, M.J., Dickie, J., Bartie, P., Brown, C., Oliver, D.M., 2023. Understanding health outcomes from exposure to blue space resources: towards a mixed methods framework for analysis. Resources 12 (11), 135.

Gül, M.R., 2023. Short-term tourism alters abundance, size, and composition of microplastics on sandy beaches. Environ. Pollut. 316, 120561.

Halliday, E., Gast, RJ., 2011. Bacteria in beach sands: An emerging challenge in protecting coastal water quality and bather health. Environ. Sci. Technol. 45, 370–379.

He, D., Luo, Y., Lu, S., Liu, M., Song, Y., Lei, L., 2018. Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC Trends Anal. Chem. 109, 163–172.

Holmberg, T., Ideland, M., 2023. The (in) visibility of sewage management and problematization as strategy for public awareness. Sociol. Rev. 71 (3), 696–715.

Holmes, J., Clark, R., 2008. Enhancing the use of science in environmental policy-making and regulation. Environ. Sci. Policy 11 (8), 702–711.

Jago, C., Robins, P., Howlett, E., Hassard, F., Rajko-Nenow, P., Jackson, S., Chien, N., Malham, S., 2024. Trapping and bypassing of suspended particulate matter, particulate nutrients and faecal indicator organisms in the river-estuary transition zone of a shallow macrotidal estuary. Sci. Total Environ. 917, 170343.

Jiang, J.J., Hanun, J.N., Chen, K.Y., Hassan, F., Liu, K.T., Hung, Y.H., Chang, T.W., 2023. Current levels and composition profiles of microplastics in irrigation water. Environ. Pollut. 318, 120858.

Jorgensen, B., Krasny, M., Baztan, J., 2021. Volunteer beach cleanups: civic environmental stewardship combating global plastic pollution. Sustain. Sci. 16 (1), 153–167.

Jose, S., Lonappan, L., Cabana, H., 2024. Prevalence of microplastics and fate in wastewater treatment plants: a review. Environ. Chem. Lett. 1–34.

Kay, D., Bartram, J., Prüss, A., Ashbolt, N., Wyer, M.D., Fleisher, J.M., Fewtrell, L., Rogers, A., Rees, G., 2004. Derivation of numerical values for the World Health Organization guidelines for recreational waters. Water Res. 38 (5), 1296–1304.

Kevill, J.L., Farkas, K., Ridding, N., Woodhall, N., Malham, S.K., Jones, D.L., 2023. Use of capsid integrity-qPCR for detecting viral capsid integrity in wastewater. Viruses 16 (1), 40.

Kroeze, C., Gabbert, S., Hofstra, N., Koelmans, A.A., Li, A., Löhr, A., Ludwig, F., Strokal, M., Verburg, C., Vermeulen, L., van Vliet, M.T., 2016. Global modelling of surface water quality: a multi-pollutant approach. Curr. Opin. Environ. Sustain. 23, 35–45.

Koelmans, A.A., Redondo-Hasselerharm, P.E., Nor, N.H.M., de Ruijter, V.N., Mintenig, S.M., Kooi, M., 2022. Risk assessment of microplastic particles. Nat. Rev. Mater. 7 (2), 138–152.

Kurniawan, T.A., Haider, A., Mohyuddin, A., Fatima, R., Salman, M., Shaheen, A., Ahmad, H.M., Al-Hazmi, H.E., Othman, M.H.D., Aziz, F., Anouzla, A., 2023. Tackling microplastics pollution in global environment through integration of applied technology, policy instruments, and legislation. J. Environ. Manag. 346, 118971.

Kutralam-Muniasamy, G., Pérez-Guevara, F., Shruti, V.C., 2022. (Micro) plastics: a possible criterion for beach certification with a focus on the blue flag award. Sci. Total Environ. 803, 150051.

Leonard, A.F., Singer, A., Ukoumunne, O.C., Gaze, W.H., Garside, R., 2018. Is it safe to go back into the water? A systematic review and meta-analysis of the risk of acquiring infections from recreational exposure to seawater. Int. J. Epidemiol. 47, 572–586.

Li, S., Ding, F., Flury, M., Wang, Z., Xu, L., Li, S., Jones, D.L., Wang, J., 2022. Macro-and microplastic accumulation in soil after 32 years of plastic film mulching. Environ. Pollut. 300, 118945.

Liu, P., Dai, J., Huang, K., Yang, Z., Zhang, Z., Guo, X., 2023. Sources of micro (nano) plastics and interaction with co-existing pollutants in wastewater treatment plants. Crit. Rev. Environ. Sci. Technol. 53, 865–885.

Locatelli, L., Russo, B., Acero Oliete, A., Sánchez Catalán, J.C., Martínez-Gomariz, E., Martínez, M., 2020. Modeling of *E. coli* distribution for hazard assessment of bathing waters affected by combined sewer overflows. Nat. Hazards Earth Syst. Sci. 20 (5), 1219–1232.

Luo, G., Liang, B., Cui, H., Kang, Y., Zhou, X., Tao, Y., Lu, L., Fan, L., Guo, J., Wang, A., Gao, S.H., 2023. Determining the contribution of micro/nanoplastics to antimicrobial resistance: challenges and perspectives. Environ. Sci. Technol. 57 (33), 12137–12152.

Magalhães, E.A., de Jesus, H.E., Pereira, P.H.F., Gomes, A.S., Dos Santos, H.F., 2024. Beach sand plastispheres are hotspots for antibiotic resistance genes and potentially pathogenic bacteria even in beaches with good water quality. Environ. Pollut. 344, 123237.

Mayer, P.M., Moran, K.D., Miller, E.L., Brander, S.M., Harper, S., Garcia-Jaramillo, M., Carrasco-Navarro, V., Ho, K.T., Burgess, R.M., Hampton, L.M.T., Granek, E.F., 2024. Where the rubber meets the road: Emerging environmental impacts of Tire Wear particles and their chemical cocktails. Sci. Total Environ., 171153

Metcalf, R., White, H.L., Moresco, V., Ormsby, M.J., Oliver, D.M., Quilliam, R.S., 2022a. Sewage-associated plastic waste washed up on beaches can act as a reservoir for faecal bacteria, potential human pathogens, and genes for antimicrobial resistance. Mar. Pollut. Bull. 180, 113766.

Metcalf, R., Oliver, D.M., Moresco, V., Quilliam, R.S., 2022b. Quantifying the importance of plastic pollution for the dissemination of human pathogens: The challenges of choosing an appropriate 'control' material. Sci. Total Environ. 810, 152292.

Metcalf, R., White, H.L., Ormsby, M.J., Oliver, D.M., Quilliam, R.S., 2023. From wastewater discharge to the beach: Survival of human pathogens bound to microplastics during transfer through the freshwater-marine continuum. Environ. Pollut. 319, 120955.

Mehinto, A.C., Coffin, S., Koelmans, A.A., Brander, S.M., Wagner, M., Thornton Hampton, L.M., Burton Jr., A.G., Miller, E., Gouin, T., Weisberg, S.B., Rochman, C. M., 2022. Risk-based management framework for microplastics in aquatic ecosystems. Microplast. nanoplast. 2 (1), 17.

Metcalf, R., Akinbobola, A., Quilliam, RS., 2024a. Isolation of human pathogenic Candida species colonising plastic wastes: environmental screening for drug resistance, thermotolerance, and virulence of 'WHO Priority Fungal Pathogens'. Scientific Reports (In review).

Metcalf, R., Fellows, R., White, H.L., Quilliam, R.S., 2024b. Persistence of 'wet wipes' in beach sand: An unrecognised reservoir for localised *E. coli* contamination. Mar. Pollut. Bull. 201, 116175.

Monira, S., Roychand, R., Bhuiyan, M.A., Pramanik, B.K., 2023. Role of water shear force for microplastics fragmentation into nanoplastics. Environ. Res., 116916

Moresco, V., Charatzidou, A., Oliver, D.M., Weidmann, M., Matallana-Surget, S., Quilliam, R.S., 2022. Binding, recovery, and infectiousness of enveloped and non-enveloped viruses associated with plastic pollution in surface water. Environ. Pollut. 308, 119594.

Moresco, V., Oliver, D.M., Weidmann, M., Matallana-Surget, S., Quilliam, R.S., 2021. Survival of human enteric and respiratory viruses on plastics in soil, freshwater, and marine environments. Environ. Res. 199, 111367.

Müller, A., Österlund, H., Marsalek, J., Viklander, M., 2020. The pollution conveyed by urban runoff: A review of sources. Sci. Total Environ. 709, 136125.

Müller, N.D., Kirtane, A., Schefer, R.B., Mitrano, D.M., 2024. eDNA adsorption onto microplastics: impacts of water chemistry and polymer physiochemical properties. Environ. Sci. Technol.

Nelms, S.E., Easman, E., Anderson, N., Berg, M., Coates, S., Crosby, A., Eisfeld-Pierantonio, S., Eyles, L., Flux, T., Gilford, E., Giner, C., 2022. The role of citizen science in addressing plastic pollution: Challenges and opportunities. Environ. Sci. Policy 128, 14–23.

Nyberg, B., Harris, P.T., Kane, I., Maes, T., 2023. Leaving a plastic legacy: Current and future scenarios for mismanaged plastic waste in rivers. Sci. Total Environ. 869, 161821.

Oliver, D.M., Van Niekerk, M., Kay, D., Heathwaite, A.L., Porter, J., Fleming, L.E., Kinzelman, J.L., Connolly, E., Cummins, A., McPhail, C., Rahman, A., 2014. Opportunities and limitations of molecular methods for quantifying microbial compliance parameters in EU bathing waters. Environ. Int. 64, 124–128.

Oliver, D.M., Porter, K.D., Pachepsky, Y.A., Muirhead, R.W., Reaney, S.M., Coffey, R., Kay, D., Milledge, D.G., Hong, E., Anthony, S.G., Page, T., 2016a. Predicting microbial water quality with models: over-arching questions for managing risk in agricultural catchments. Sci. Total Environ. 544, 39–47.

Oliver, D.M., Hanley, N.D., Van Niekerk, M., Kay, D., Heathwaite, A.L., Rabinovici, S.J., Kinzelman, J.L., Fleming, L.E., Porter, J., Shaikh, S., Fish, R., et al., 2016b. Molecular tools for bathing water assessment in Europe: Balancing social science research with a rapidly developing environmental science evidence-base. Ambio 45, 52–62.

Ormsby, M.J., White, H.L., Metcalf, R., Oliver, D.M., Quilliam, R.S., 2023. Clinically important *E. coli* strains can persist, and retain their pathogenicity, on environmental plastic and fabric waste. Environ. Pollut. 326, 121466.

Pascoe, S., 2019. Recreational beach use values with multiple activities. Ecol. Econ. 160, 137–144.

Perry, W.B., Ahmadian, R., Munday, M., Jones, O., Ormerod, S.J., Durance, I., 2024. Addressing the challenges of combined sewer overflows. Environ. Pollut., 123225

Phan, S., Luscombe, C.K., 2023. Recent trends in marine microplastic modeling and machine learning tools: Potential for long-term microplastic monitoring. J. Appl. Phys. 133 (2).

Qi, R., Jones, D.L., Li, Z., Liu, Q., Yan, C., 2020. Behavior of microplastics and plastic film residues in the soil environment: A critical review. Sci. Total Environ. 703, 134722.

Quilliam, R.S., Pow, C.J., Shilla, D.J., Mwesiga, J.J., Shilla, D.A., Woodford, L., 2023. Microplastics in agriculture–a potential novel mechanism for the delivery of human pathogens onto crops. Front. Plant Sci. 14, 1152419.

Richon, C., Kvale, K., Lebreton, L., Egger, M., 2023. Legacy oceanic plastic pollution must be addressed to mitigate possible long-term ecological impacts. Microplastics Nanoplastics 3 (1), 25.

Robins, P.E., Dickson, N., Kevill, J.L., Malham, S.K., Singer, A.C., Quilliam, R.S., Jones, D.L., 2022. Predicting the dispersal of SARS-CoV-2 RNA from the wastewater treatment plant to the coast. Heliyon 8 (9).

Rodrigues, A., Oliver, D.M., McCarron, A., Quilliam, R.S., 2019. Colonisation of plastic pellets (nurdles) by *E. coli* at public bathing beaches. Mar. Pollut. Bull. 139, 376–380.

Saliba, M., Frantzi, S., van Beukering, P., 2022. Shipping spills and plastic pollution: A review of maritime governance in the North Sea. Mar. Pollut. Bull. 181, 113939.

Sánchez-García, C., Button, E.S., Wynne-Jones, S., Porter, H., Rugg, I., Hannam, J.A., 2023. Finding common ground: Co-producing national soil policy in Wales through academic and government collaboration. Soil Secur. 11, 100095.

Schell, T., Hurley, R., Buenaventura, N.T., Mauri, P.V., Nizzetto, L., Rico, A., Vighi, M., 2022. Fate of microplastics in agricultural soils amended with sewage sludge: Is surface water runoff a relevant environmental pathway? Environ. Pollut. 293, 118520.

Shafi, M., Lodh, A., Khajuria, M., Ranjan, V.P., Gani, K.M., Chowdhury, S., Goel, S., 2024. Are we underestimating stormwater? Stormwater as a significant source of microplastics in surface waters. J. Hazard. Mater., 133445

Shafea, L., Yap, J., Beriot, N., Felde, V.J., Okoffo, E.D., Enyoh, C.E., Peth, S., 2023. Microplastics in agroecosystems: A review of effects on soil biota and key soil functions. J. Plant Nutr. Soil Sci. 186 (1), 5–22.

Silva, I., Rodrigues, E.T., Tacão, M., Henriques, I., 2023. Microplastics accumulate priority antibiotic-resistant pathogens: evidence from the riverine plastisphere. Environ. Pollut. 332, 121995.

Soares, A., 2020. Wastewater treatment in 2050: Challenges ahead and future vision in a European context. Environ. Sci. Ecotechnol. 2, 100030.

Solo-Gabriele, H.M., Harwood, V.J., Kay, D., Fujioka, R.S., Sadowsky, M.J., Whitman, R. L., Wither, A., Caniça, M., Carvalho da Fonseca, R., Duarte, A., Edge, T.A., Gargaté, M.J., Gunde-Cimerman, N., Hagen, F., McLellan, S.L., Nogueira da Silva, A., Novak Babič, M., Prada, S., Rodrigues, R., Romão, D., Sabino, R., Samson, R.A., Segal, E., Staley, C., Taylor, H.D., Veríssimo, C., Viegas, C., Barroso, H., Brandão, J. C., 2016. Beach sand and the potential for infectious disease transmission: observations and recommendations. J. Mar. Biol. Assoc. U. K. 96, 101–120.

Stride, B., Abolfathi, S., Bending, G.D., Pearson, J., 2024. Quantifying microplastic dispersion due to density effects. J. Hazard. Mater. 466, 133440.

Varvastian, S., 2023. The role of courts in plastic pollution governance. Int. Comp. Law Q. 72 (3), 635–669.

Vass, M., Ramasamy, K.P., Andersson, A., 2024. Microbial hitchhikers on microplastics: The exchange of aquatic microbes across distinct aquatic habitats. Environ. Microbiol. 26 (4), e16618.

Vethaak, A.D., Leslie, H.A., 2016. Plastic debris is a human health issue. ES&T 13, 6825–6826, 2016, 50.

Wang, S., 2023. International law-making process of combating plastic pollution: status quo, debates and prospects. Mar. Policy 147, 105376.

Water UK, 2023. Fine to flush certification to end. https://www.water.org.uk/news-views-publications/news/fine-flush-certification-end#:~:text=The%20Fine%20to%20Flush%20'wet,an%20end%20in%20March%202024. Accessed 18th April 2024.

Watts, A.J., Porter, A., Hembrow, N., Sharpe, J., Galloway, T.S., Lewis, C., 2017. Through the sands of time: beach litter trends from nine cleaned North Cornish beaches. Environ. Pollut. 228, 416–424.

Whelan, M.J., Linstead, C., Worrall, F., Ormerod, S.J., Durance, I., Johnson, A.C., Johnson, D., Owen, M., Wiik, E., Howden, N.J., Burt, T.P., 2022. Is water quality in British rivers "better than at any time since the end of the industrial revolution? Sci. Total Environ. 843, 157014.

White, H.L., Mwapasa, T., Mphasa, M., Kalonde, P.K., Feasey, N., Oliver, D.M., Ormsby, M.J., Morse, T., Chidziwisano, K., Quilliam, R.S., 2023. Open defaecation by proxy: Tackling the increase of disposable diapers in waste piles in informal settlements. Int. J. Hyg. Environ. Health 250, 114171.

Whitman, R.L., Harwood, V.J., Edge, T.A., Nevers, M.B., Byappanahalli, M., Vijayavel, K., Brandao, J., Sadowsky, M.J., Alm, E.W., Crowe, A., Ferguson, D., Ge, Z.F., Halliday, E., Kinzelman, J., Kleinheinz, G., Przybyla-Kelly, K., Staley, C., Staley, Z., Solo-Gabriele, HM., 2014. Microbes in beach sands: Integrating environment, ecology and public health. Rev. Environ. Sci. Bio Technol. 13, 329–368.

Witsø, I.L., Basson, A., Vinje, H., Llarena, A.K., Bringas, C.S., Aspholm, M., Wasteson, Y., Myrmel, M., 2023. Freshwater plastispheres as a vector for foodborne bacteria and viruses. Environ. Microbiol. 25 (12), 2864–2881.

Wright, L.S., Napper, I.E., Thompson, R.C., 2021. Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density. Mar. Pollut. Bull. 173, 113115.

Zadjelovic, V., Wright, R.J., Borsetto, C., Quartey, J., Cairns, T.N., Langille, M.G., Wellington, E.M., Christie-Oleza, J.A., 2023. Microbial hitchhikers harbouring antimicrobial-resistance genes in the riverine plastisphere. Microbiome 11 (1), 225.

Zan, R., Blackburn, A., Plaimart, J., Acharya, K., Walsh, C., Stirling, R., Kilsby, C.G., Werner, D., 2023. Environmental DNA clarifies impacts of combined sewer overflows on the bacteriology of an urban river and resulting risks to public health. Sci. Total Environ. 889, 164282.

Zeb, A., Liu, W., Ali, N., Shi, R., Wang, Q., Wang, J., Li, J., Yin, C., Liu, J., Yu, M., Liu, J., 2023. Microplastic pollution in terrestrial ecosystems: Global implications and sustainable solutions. J. Hazard. Mater., 132636

Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A, 2013. Life in the "plastisphere": microbial communities on plastic marine debris. Environ. Sci. Technol. 47.

Zhang, L., Zhao, W., Yan, R., Yu, X., Barceló, D., Sui, Q., 2024. Microplastics in different municipal solid waste treatment and disposal systems: do they pose environmental risks? Water Res., 121443

Zhong, H., Wu, M., Sonne, C., Lam, S.S., Kwong, R.W., Jiang, Y., Zhao, X., Sun, X., Zhang, X., Li, C., Li, Y., 2023. The hidden risk of microplastic-associated pathogens in aquatic environments. Eco-Environ. Health 2, 142–151.

Zuccaro, P., Thompson, D.C., de Boer, J., Llompart, M., Watterson, A., Bilot, R., Birnbaum, L.S., Vasiliou, V., 2024. The European union ban on microplastics includes artificial turf crumb rubber infill: other nations should follow suit. Environ. Sci. Technol. 58, 2591–2594.