Journal of Future Agrisphere Vol 1(1)

Review

Sources impacts and mitigation strategies of microplastic contamination in laboratory environments

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Received: 14 June 2024
Revised: 29 July 2024
Accepted: 11 August 2024
Published: 24 August 2024

Subject: Plant Science

Academic editor: Shahzad Munir

DOI:

Abstract

The spread of microplastics has become a major environmental issue in recent years with potentially devastating impacts on ecosystems and human health. While considerable focus has been on the visible effects of microplastic pollution but their presence and influence within laboratory environments have been less understood. This review examines the sources and routes of microplastic contamination in laboratory settings, emphasizing their intentional and unintentional introduction through laboratory equipment, materials, and environmental exposure. This paper assesses the potential impacts of microplastic contamination on cellular well-being including implications for experimental outcomes and research methodologies. This paper further investigates the challenges in detecting and preventing microplastic contamination in the laboratory, underscoring the need for standardized procedures and advanced detection techniques. By synthesizing current literature this study provides a comprehensive analysis of the risks posed by microplastics in laboratory environments and suggests strategies to mitigate their influence on scientific research.

Keywords: Microplastic, Laboratory, Standardization Protocols, Environmental Contamination, Cellular Health.

Introduction

Microplastics are widespread pollutants found in the environment and are defined as plastic particles smaller than five millimeters in size, have spread across the entire planet, posing a widespread challenge to environmental sustainability (da Costa et al. 2017). They come from various sources such as the breakdown of larger plastic waste, microbeads in personal care products, and synthetic textile fibers (Hale et al. 2020). These tiny pollutants have become deeply embedded in modern life and can be found in various ecosystems including marine environments, freshwater systems (Campanale et al. 2020), soil (Rillig et al. 2017), air (Prata, 2018), and organisms (Rezania et al. 2018) throughout the biological spectrum (Gavrilescu et al. 2015).

Microplastic's extensive presence highlights the pressing requirement for an in-depth understanding and measures to reduce its impact. Investigations into their presence within laboratory environments have garnered substantial interest and far-reaching implications beyond just contamination. Whether introduced through laboratory equipment, supplies, or environmental factors, microplastics do not merely remain passive within the lab setting. Instead, they can actively interact with experimental systems, particularly in cell-based assays, where their influence may alter cellular responses and jeopardize the reliability of scientific findings (Jones et al.

2024).

Emerging research has revealed diverse sources of microplastic contamination in laboratory settings, ranging from airborne particles to water and consumable materials. This contamination may originate from the utilization of plastic labware, which has demonstrated superior performance compared to glassware in specific applications, yet still introduces microplastic pollutants (Mills et al. 2023). Notably, a recent study has underscored that any experimental activities inherently introduce microplastic and nanoplastic contaminants, underscoring the critical need for robust quality control measures to ensure the reliability of research outcomes in this field. Furthermore, biological safety cabinets have failed to substantially mitigate contamination levels, suggesting that microplastic presence is an inherent challenge within laboratory settings (Jones et al. 2024).

Microplastic contaminants can undermine the validity of laboratory findings. Their presence can bias the results of toxicological studies and other experimental investigations. For instance, a review of in vivo studies using laboratory rodents revealed a marked disparity between the concentrations of microplastics administered in experiments and those detected in natural environments, emphasizing the need for more ecologically representative studies. This discrepancy implies that the effects observed in controlled laboratory settings may not accurately reflect real-world scenarios, thereby complicating our understanding of the health impacts of microplastics (Mills et al. 2023).

Microplastic's interaction with experimental systems, particularly in cell-based studies, may alter cellular behavior and compromise the integrity of scientific research. Comprehending how microplastics can affect cellular health is crucial, as even minute quantities can lead to significant changes in cell viability, function, and experimental outcomes (Jones et al. 2024). This cellular interaction with microplastics is not only relevant for laboratory settings but also reflect broader environmental and health implications. Understanding the mechanisms of microplastic uptake by cells can provide insights into their potential impacts on human health and ecological systems, as analogous processes may occur in natural environments. Addressing microplastic contamination in laboratories is thus crucial, as it serves as a microcosm for larger environmental concerns, rendering the discussion pertinent to both the scientific community and public health stakeholders (Ali et al. 2024). This connection underscores the necessity for a more in-depth investigation into the biological ramifications of microplastic contamination within laboratory settings, linking environmental concerns with the fundamental aspects of biomedical research (Jones et al. 2024).

An especially noteworthy area of investigation revolves around the interaction between microplastics and cellular membranes, which play a critical role in maintaining biological integrity (Wang et al. 2022). Due to their minute size and chemical makeup, microplastics have an unusual ability to attract and accumulate harmful substances from the surrounding environment (Huang et al. 2021). When consumed by living organisms, these particles can interfere with the integrity of cellular membranes, impacting vital cellular processes like nutrient absorption, waste removal, and cell communication pathways. This disruption at the cellular membrane level can trigger widespread effects on biological functions, potentially causing far-reaching impacts at both individual organism and ecosystem levels (Yin et al. 2021).

Recent research has uncovered the complex ways in which microplastics cause harm within cells. Advanced imaging techniques have shown that these tiny particles are located inside cell organelles like lysosomes and mitochondria. This internal localization not only interferes with organelle operations but also induces cellular stress reactions, such as oxidative stress and inflammation (Kadac-Czapska et al. 2024). The combined effect of these disruptions can lead to various negative health effects, from lowered reproductive capability to impaired immune function in affected organisms (Sharifinia et al. 2020).

Additionally, new findings indicate that microplastics may disrupt cellular metabolism by affecting energy production pathways and changing essential biochemical processes for maintaining cellular balance (Cheng et al. 2022; Goodman et al. 2022; Ye et al. 2021). Research has shown alterations in gene expression patterns and metabolic profiles in organisms exposed to microplastics, underscoring the intricate nature of their impact on cellular functions. The repercussions of these metabolic disturbances can be extensive, impacting the growth, development, and general fitness of affected organisms (Kazmi et al. 2024).

Microplastic pollution extends beyond the scope of individual cells and presents wider ecological issues, such as changes in food chains, ecosystem functions, and natural cycles (Hale et al. 2020; Kumar et al. 2021). Microplastics can build up in higher trophic levels through processes of bioaccumulation and biomagnification, endangering predators and eventually affecting entire ecosystems (Huang et al. 2021; Alava, 2020). Moreover, the movement of microplastics through the air (Enyoh et al. 2019; O'Brien et al. 2023) and water currents enables them to disperse over long distances globally, increasing their environmental impact and complicating efforts to control them (He et al. 2021; Cai et al. 2021). The objectives of our review are to investigate the sources and pathways of microplastic contamination in laboratory environments, and to assess the impact of microplastics on cellular health and the implications for laboratory research and methodologies, and to explore challenges and strategies in detecting, preventing, and standardizing microplastic contamination in laboratory settings.

Microplastic contamination in the laboratory

Laboratory instruments and supplies are essential for conducting experimental studies, but they also carry the risk of microplastic contamination. Plastic components commonly found in laboratories can release tiny plastic particles through abrasion, leaching, and degradation. Typical consumables like pipette tips, culture dishes, flasks, and tubes are frequently made from plastic polymers, increasing the likelihood of microplastic emission during various stages of handling and use (Tan et al. 2022). Microplastic contaminants are introduced during the production process, and standard laboratory practices like washing, autoclaving, and sterilization can potentially worsen particle shedding. Furthermore, the repeated utilization and cleaning of plastic equipment can result in wear and tear, thereby increasing the possibility of microplastic contamination (Freeland et al. 2022).

Environmental introduction of microplastics

Besides the laboratory ware, environmental factors play a crucial role in the presence of microplastic contamination. For example, microplastics in the air, which come from sources such as outdoor pollution, industrial processes, and indoor settings, can enter laboratory spaces through ventilation systems, open windows, and human actions (Kacprzak and Tijing, 2022; Bhat, 2023; Chen et al. 2022). Additionally, water sources utilized for preparing media, cleaning glassware, and conducting lab procedures may harbor microplastic particles stemming from public water sources, plumbing systems, or contamination during storage and transportation. Furthermore, plastic containers and tools for laboratory activities like storing, cleaning, and personal hygiene may inadvertently add to the problem of microplastic contamination in laboratory settings (Wesch et al. 2016; Brander et al. 2020).

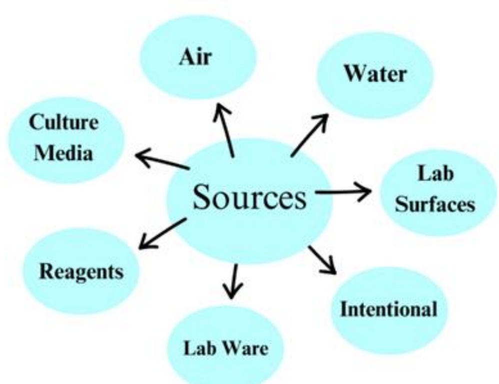

Figure 1: Microplastic sources in laboratory settings.

Methodological introduction of microplastics

Controlled laboratory experiments are commonly employed to investigate the environmental impact, biological effects, and potential mitigation strategies of microplastics. This intentional introduction of microplastics allows researchers to simulate real-world conditions and assess their interactions with various biological and ecological systems.

Experimental approaches

Laboratories may utilize specific types and concentrations of microplastics to evaluate their effects on organisms, such as fish or invertebrates. This helps elucidate the toxicological impacts and potential for bioaccumulation of microplastics in marine and freshwater environments (Cowger et al. 2020; Jones et al. 2024).

Methodological standardization:

The development of standardized protocols for the introduction and analysis of microplastics is crucial. These protocols often include detailed procedures for the preparation of microplastic samples, including size fractionation and characterization techniques like Fourier-transform infrared spectroscopy and Raman spectroscopy. Such standardization promotes reproducibility and comparability of results across different studies (Masura et al. 2015; Prata et al. 2019).

Quality assurance and control

To maintain the integrity of experiments, strict quality assurance and control measures are implemented. This includes the use of procedural blanks to quantify contamination levels and ensure accurate measurement and reporting of microplastic introduction (Campanale et al. 2020; Jones et al. 2024).

Microplastic implications in laboratory settings

Microplastics impact on cellular health

Cellular models serve as a fundamental tool in a wide range of biomedical research, encompassing areas such as drug development and toxicity testing. Any factor that influences cellular behavior or health can significantly impact the outcomes of these studies. Microplastics, even in minute amounts, can interact with cells in ways that may not be immediately apparent, yet have the potential to alter crucial cellular functions, including gene expression, protein synthesis, and cell signaling (Cassano et al. 2023). These changes can lead to inaccurate data and erroneous conclusions if not properly accounted for. Within laboratory environments, microplastic contamination can act as an unintended variable that may interfere with cellular processes. Without a thorough understanding of this interaction, researchers may incorrectly attribute changes in cellular health to other experimental factors. Disregarding the potential effects of microplastics on cellular health could undermine the reliability of experimental results, thereby compromising the integrity of the research (Prinz and Korez, 2020). Recognizing and comprehending how microplastics affect cellular health is crucial for designing experiments that can effectively control or eliminate these effects. This understanding also aids in the proper interpretation of results, ensuring that the observed outcomes are genuinely due to the intended experimental conditions rather than unintended contamination (Jones et al. 2024). Given the pivotal role of reproducibility in scientific research, acknowledging and accounting for the effects of microplastics on cellular health is essential for generating consistent and reliable results across different laboratories and studies.

Cellular uptake and accumulation

Microplastics can be internalized by cells through various mechanisms, primarily endocytosis, where cells engulf particles from their surrounding environment (Huang et al. 2022). Research has demonstrated that the uptake of microplastics is size-dependent, with smaller particles typically exhibiting higher rates of cellular internalization. For instance, polystyrene microplastics with a 1 μm diameter have shown substantial internalization in diverse cell types, with the percentage of cells containing these particles increasing over time with prolonged exposure. At a concentration of 5 μg/mL, approximately 39% of cells were found to have internalized microplastics after 24 hours, which then increased to around 64% after 72 hours. In contrast, at a higher concentration of 100 μg/mL, approximately 91% of cells had internalized microplastics within the first 24 hours, indicating a rapid uptake at elevated concentrations (Goodman et al. 2022).

Factors influencing cellular uptake

Cells' uptake of microplastics is affected by various factors, including the properties of the particles, the types of cells involved, and the surrounding environmental conditions. For example, particle size plays a crucial role in determining how effectively and through what method microplastics are taken up by cells. Phagocytic cells have an easier time engulfing larger microplastic particles while smaller ones may be internalized through pinocytosis or passive diffusion (Caputo et al. 2021). Moreover, particle shape, surface charge, and surface chemistry also impact cellular interactions and uptake rates, with hydrophobic particles tend to adhere more to cell membranes and have higher rates of internalization (Stock et al. 2022).

Cell type specificity also determines the likelihood of taking in microplastics, with immune cells like macrophages, dendritic cells, and neutrophils showing greater ability to consume compared to non-immune cells. Nonetheless, recent research has shown that different cell types such as epithelial cells, endothelial cells, and neuronal cells can internalize microplastics through endocytic processes, although the extent may vary (Rio et al. 2024; Prado et al. 2023).

Environmental conditions such as temperature, pH, and the composition of the extracellular matrix can impact how cells take in and move microplastics inside them. For example, acidic pH levels in lysosomes could speed up the breakdown of engulfed microplastics, while changes in membrane flexibility and lipid makeup can affect passive diffusion rates (Asmonaite, 2019). Additionally, the presence of serum proteins, substances secreted by cells, and components of the surrounding matrix may either encourage or hinder microplastic uptake by influencing interactions on cell surfaces and signaling pathways.

Moreover, the physical and chemical characteristics of microplastics like surface modifications, polymer structure, and absorbed pollutants play a role in cellular reactions and harmful effects (Shi et al. 2022). Microplastics covered with biofilms or communities of microbes might have different interactions with cells that result in enhanced clinging to cells, internalization into them, or immune system activation (Lehel and Murphy, 2021; Gupta et al. 2024). On the other hand, microplastics combined with toxic contaminants or chemicals that disrupt hormones could trigger stress responses within cells, cause oxidative harm, and set off inflammatory processes which would then compromise cell life span and functionality (Kadac-Czapska et al. 2024).

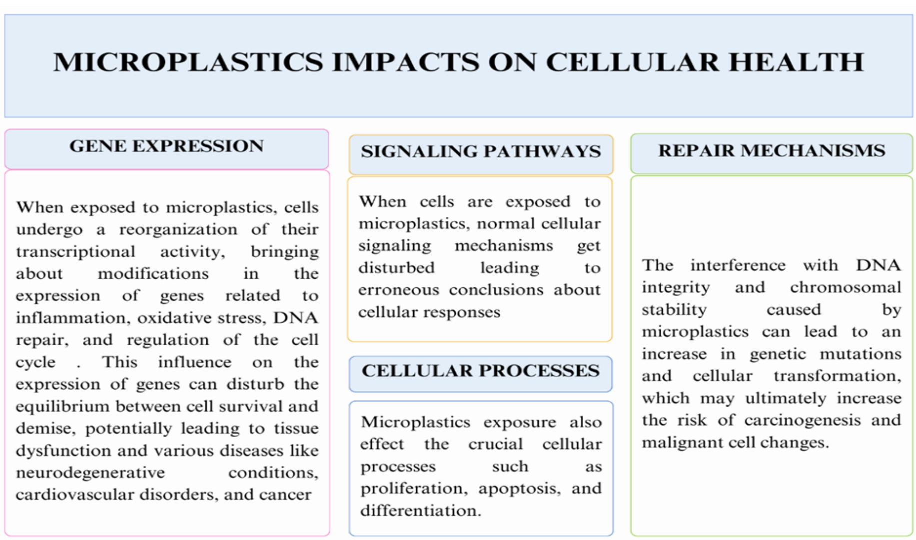

Figure 2: Impacts of microplastics on cellular health

Cellular response to microplastics

Microplastics impact gene expression, signaling pathways, and crucial cellular functions. They have been demonstrated to influence the way genes are expressed and how signaling pathways operate in various types of cells, causing changes in cellular reactions and bodily processes. When exposed to microplastics, cells undergo a reorganization of their transcriptional activity, bringing about modifications in the expression of genes related to inflammation, oxidative stress, DNA repair, and regulation of the cell cycle (Sun et al. 2021; Wang et al. 2022).

One regular cellular response to microplastic exposure is the activation of pro-inflammatory signaling pathways, such as nuclear factor-kappa B (NF-κB) and mitogen-activated protein kinases (MAPKs). In response to environmental pressures, these pathways are essential for coordinating immune responses, cytokine generation, and tissue remodeling (Qi et al. 2021). Microplastics induce the production of pro-inflammatory cytokines, chemokines, and adhesion molecules which then lead to the start and spread of inflammatory sequences within impacted tissues (Pechiappan, 2021; Del Piano et al. 2023).

In addition, microplastics can disturb DNA repair mechanisms, telomere maintenance, and epigenetic regulation, causing genomic instability and irregular gene expression profiles. This interference with DNA integrity and chromosomal stability caused by microplastics can lead to an increase in genetic mutations and cellular transformation, which may ultimately increase the risk of carcinogenesis and malignant cell changes. Microplastics not only impact gene expression and signaling pathways but also have significant effects on crucial cellular processes such as proliferation, apoptosis, and differentiation. The disturbance of these functions leads to cellular dysfunction, tissue injury, and the development of diseases (Bucaite et al. 2023).

Microplastics influence cellular proliferation by changing the progression of cell cycles, DNA replication, and dynamics of mitotic spindles. Depending on the specific traits of the particles and the surrounding cellular environment, microplastics may prompt either increased or decreased cell growth effects, resulting in disrupted tissue homeostasis (Gao et al. 2021). Apoptosis, also known as programmed cell death, plays a crucial role in removing defective or irregular cells to preserve tissue health and balance. Research suggests that microplastics may interfere with the normal regulation of apoptotic processes, impacting the survival or elimination of cells. This influence on the expression of genes can disturb the equilibrium between cell survival and demise, potentially leading to tissue dysfunction and various diseases like neurodegenerative conditions, cardiovascular disorders, and cancer (Lu et al. 2024; Pluciennik et al. 2024). In conclusion, comprehensively investigating microplastic contamination in laboratory environments necessitates considering the cellular health perspective, as it offers a holistic understanding of how these particles may impact experimental outcomes at the most fundamental level. The implications of microplastics extend beyond the physical environment, permeating the underlying biological systems. By addressing cellular health, one can consider both the direct and indirect ramifications of microplastic contamination, which is crucial for devising effective mitigation strategies.

Impact on experimental validity

The presence of microplastics in laboratory settings can significantly compromise the experimental validity. Microplastics can introduce unaccounted variables, leading to skewed results, particularly in sensitive assays such as toxicity testing and drug efficacy studies. For example, a study demonstrated that contamination from common laboratory procedures, including the use of unburnt glassware and water sources, can introduce microplastics into samples, potentially altering the conclusions drawn from experiments (Aminah and Ikejima, 2023). Researchers have also found that microplastics present in laboratory air and dust could affect cellular responses, resulting in misinterpretation of the effects of tested substances. This emphasizes the necessity for researchers to consider microplastic contamination as a critical factor in their experimental designs and analyses (Jones et al. 2024).

Challenges in reproducibility

The presence of microplastics in laboratory environments poses a significant threat to the reproducibility of scientific experiments, which is a fundamental principle of credible research. Varied sampling methodologies across laboratories, such as the use of nets with different mesh sizes, can lead to discrepancies in measured microplastic levels. This size-selective nature of sampling techniques may result in the under- or over-estimation of microplastic abundance, consequently skewing the comparability of findings across studies (Weis and Palmquist, 2021). The analytical methods utilized by different laboratories to identify and enumerate microplastics can vary considerably. For example, some laboratories may rely on optical microscopy, while others employ more sophisticated techniques such as micro-Raman spectroscopy or scanning electron microscopy. This methodological heterogeneity can result in divergent determinations of microplastic types and abundances, ultimately affecting the overall conclusions derived from multi-institutional studies (Bhat, 2024; Cormier et al. 2019). Additionally, fluctuations in microplastic contamination levels over time, driven by factors such as changes in plastic usage and waste management practices, can pose challenges for long-term studies. Failure to account for these temporal variations may result in inconsistent findings, hindering the accurate assessment of long-term trends. For example, a multi-year investigation may encounter dynamic contamination levels, complicating the analysis of long-term patterns and developments (Ziani et al. 2023). Variation in background contaminants associated with microplastics across different studies can contribute to inconsistent findings. For instance, if microplastic samples from one laboratory are contaminated with pollutants such as oxybenzone or benzopyrene, while samples from another laboratory are not, the resulting data on toxicity and environmental impacts could differ significantly. This variability in contaminant profiles would lead to disparities in the conclusions drawn from these studies (Cormier et al. 2019).

Impact on methodological design

Microplastic identification and quantification can be hindered by contamination, complicating the differentiation between environmental and laboratory-derived samples. This challenge requires the implementation of robust control measures and meticulous methodological approaches to maintain data reliability (Loder and Gerdts, 2015) Researchers must increasingly implement new control measures or redesign studies to account for or mitigate the effects of microplastic interference. For example, it is recommended that laboratories employ microplastic-free consumables and establish rigorous contamination control procedures, such as conducting experiments in clean rooms or utilizing biological safety cabinets (Campanale et al. 2020). Furthermore, researchers may need to incorporate contamination as an experimental variable, enabling a more accurate assessment of the phenomena under investigation. This proactive approach is crucial for preserving the integrity and reliability of research findings.

Considerations for data interpretation

Microplastic contamination can complicate the interpretation of experimental data, as it has the potential to influence cellular responses and overall experimental outcomes. Failure to account for the effects of microplastics may lead researchers to incorrectly attribute observed effects to other experimental factors, resulting in inaccurate conclusions (Jones et al. 2024). For instance, a study has demonstrated that microplastics can interfere with the biological reactions of cells, which could be mistakenly attributed to the primary variables under investigation if the issue of contamination is not acknowledged (Aminah and Ikejima, 2023). Therefore, researchers must recognize and properly address potential microplastic contamination when analyzing their data, to ensure that their interpretations accurately reflect the true experimental conditions.

Long-term implications for biomedical research

The widespread presence of microplastics in laboratory settings can have profound implications for biomedical research. Ongoing contamination issues may undermine trust in research findings, impeding scientific advancement and necessitating more rigorous regulations and oversight in laboratory environments. As awareness of microplastic pollution increases, researchers may face heightened scrutiny regarding the integrity of their results, particularly in fields such as toxicology and pharmacology where microplastics could significantly influence experimental outcomes (Aminah and Ikejima, 2023). Future research should prioritize the development of standardized protocols for contamination control, the enhancement of detection methods, and the further investigation of microplastics' effects on biological systems to fully comprehend their impact within laboratory settings.

WAKs control a variety of pathogen hosts, including race-specific, extracellular and intracellular and pathogen attack on single and multiple plant species (Stephens et al. 2022). In Arabidopsis, the AtWAK1 gene enhanced resistance to Botrytis cinerea, confirming their role in plant immunity. AtWAKL22-RFO1 is required for resistance against Fusarium oxysporum 1 (RFO1). WAKL22-ROF1 activates the Mitogen-Activated Protein Kinase (MAPK) signaling cascade and senses pectin methylation, providing early defense against the pathogen (Huerta et al., 2023).

Race-specific resistance to Leptosphaeria maculans and Zymoseptoria tritici is conferred by WAKL genes Rlm9 and Stb6 in Brassica and wheat, respectively (Larkan et al., 2020; Saintenac et al., 2018). Xanthomonas oryzae (Xoo) is managed by a race-specific, durable resistance WAK gene, Xa4, which modulates the CesA expression to facilitate cellulose biosynthesis and provide resistance against Xoo, and is also involved in cell wall enforcement (Hu et al. 2017). For chitin-induced responses, GhWAK7A interacts with chitin receptors and activates a signaling system against Verticillium dahliae (Vd) and Fusarium oxysporum in cotton (Wang et al. 2020). Additionally, GhWAK7 is not involved in oligogalacturonides (OG) responses, as it does not affect MAPK activation or ROS production.

In maize (Zea mays), early studies identified different Ht loci (Ht1, Ht2 and Ht3), with the Htn1 gene providing resistance against northern corn leaf blight (NCLB). It was later found to encode a WAK-associated protein (ZmWAK-RLK1), which is involved in delayed lesion formation of NCLB (Yang et al. 2021). Another gene ZmWAK/qHSR1, highly expressed in the maize mesocotyl, confers quantitative resistance against head smut by promoting the salicylic acid pathway (Zuo et al. 2015). WAKs that confer disease resistance through cell wall modification also modifies composition of the cell wall as an additional role, with an increase in strength of cell wall to prevent pathogen penetration during disease occurrence. ZmWAK/qHSR1 is involved in cell turgor regulation and osmotic stress tolerance, which promotes cell growth, whereas, in rice, Xa-mediated resistance to Xoo increases the expression of CesA genes, leading to increased mechanical strength.

Managing microplastic contamination in laboratories: detection, prevention, and standardization

Microplastic contamination detection

As the universality of microplastic contamination increases, precise and authentic detection methods are crucial for comprehending its impact on the environment and lessening its consequences.

Detection techniques

Microscopic Techniques: Microscopic techniques, such as optical, scanning electron, and transmission electron microscopy, have been essential for detecting and characterizing microplastics. These methods provide detailed visual information on microplastic dimensions, structure, and surface properties (Kalaronis et al. 2022; Fu et al. 2020). Additionally, researchers are developing innovative approaches, including automated image analysis and machine learning, to enhance the efficiency and accuracy of microplastic detection (Cowger et al. 2020). These advancements are supporting large-scale monitoring and improving our understanding of microplastic distribution and abundance in the environment.

Spectroscopic and chromatographic methods

Spectroscopic and chromatographic methods are valuable tools for analyzing microplastics. Fourier-transform infrared spectroscopy and Raman spectroscopy provide molecular fingerprints to differentiate plastic polymers from other materials (Cowger et al. 2020). These techniques can quantify chemical bonds and identify molecular vibrations, enabling precise analysis of microplastic composition (Jung et al. 2018; Ribeiro-Claro et al. 2017). Chromatographic methods, such as gas and liquid chromatography-mass spectrometry, can also identify and measure plastic additives, breakdown substances, and impurities, providing insights into the makeup and fate of microplastics in the environment (Akoueson et al. 2021; Ainali et al. 2021).

Emerging technologies in microplastic detection

Recent advances in nanotechnology, sensors, and imaging have revolutionized microplastic detection. Nanoparticle-based sensors and microscopy techniques enable real-time monitoring and spatial analysis of microplastics in environmental and biological samples (Velez-Escamilla and Contreras-Torres, 2022). Additionally, portable solutions like microfluidics and lab-on-a-chip platforms facilitate on-site identification and continuous environmental surveillance (Zhu et al. 2022; Farre, 2020). DNA-based methods also show promise for the rapid detection and characterization of microplastics using molecular probes and biosensors (Demeter et al. 2023; Pathan et al. 2020).

Challenges in detecting microplastic contamination

Sources of microplastic contamination: Laboratory environments can become contaminated with microplastics from various sources, including airborne particles, consumables, and materials used for sample preparation. Research indicates that microplastic contamination is a widespread issue, complicating the accurate detection and quantification of these particles in experimental samples (Jones et al. 2024).

Limitations in microplastic detection

Different analytical methods possess varying sensitivities and size detection limits, leading to discrepancies in reported contamination levels. For instance, while μ-FTIR can detect particles as small as 2.7 μm, flow cytometry can identify particles down to 200 nm. This variability in detection capabilities can significantly influence the perceived extent of microplastic contamination in experimental samples (Jones et al. 2024).

Airborne microplastic contamination

Airborne microplastics pose a persistent challenge, as they can settle on samples during processing. Even with rigorous laboratory protocols, airborne contamination can still occur, necessitating continuous evaluation and improvement of measures to control microplastic contamination (Wesch et al, 2017; Paiva et al. 2022).

Microplastic contamination prevention

Challenges in preventing microplastic contamination in the laboratory

Researchers face several key challenges in preventing microplastic contamination in laboratory settings:

Ubiquity of microplastics

Microplastics are ubiquitous in various environments, including indoor air, making it extremely challenging to completely avoid contamination. Even with the implementation of stringent protocols, some degree of contamination is often introduced through experimental procedures and materials (Prata et al. 2021).

Multiple contamination sources

Microplastics can infiltrate samples from diverse sources, such as airborne particles, plastic laboratory equipment, and materials used for sample preparation. Identifying and controlling all potential sources of contamination is a formidable task (Paiva et al. 2022).

Lack of standardized methods

The absence of harmonized and standardized methods for contamination prevention hinders researchers from implementing effective, validated protocols (Prata et al. 2024). Developing and adopting consistent best practices across the field remains an ongoing challenge.

Limitations of detection methods

Different microplastic detection techniques have varying size detection limits, which can lead to inconsistencies in reported contamination levels. For instance, μ-FTIR can detect particles ≥2.7 μm, while flow cytometry can detect ≥200 nm. Selecting the appropriate method for the specific research question is crucial (Jones et al. 2024).

Airborne contamination persistence

Airborne microplastics can persistently settle on samples during processing, even with strict protocols in place. Continuous evaluation and improvement of contamination control measures are necessary to mitigate this issue (Jones et al. 2024).

Balancing contamination reduction and sample integrity

Some contamination prevention measures, such as the use of clean-air devices, may necessitate significant changes to experimental procedures and sample handling (Paiva et al. 2022). Researchers must carefully balance the need for contamination reduction with the preservation of sample integrity and representative results.

Figure 3: Strategies to prevent microplastic contamination in laboratory.

Strategies to prevent microplastic contamination

Implementing strict practices in laboratory environments is essential for preventing contamination and reducing the transmission of microplastics (Rodrigues et al. 2019). Key strategies include:

Equipment and consumable selection

Research suggests prioritizing non-plastic laboratory instruments and supplies to minimize microplastic pollution. When plastic products are necessary, opt for high-quality options with minimal particulate release and regularly check for wear and deterioration to control the spread of microplastics during experiments (Jones et al. 2024).

Sample handling and processing

Using clean tools and non-plastic containers when collecting, preparing, and analyzing samples can minimize the risk of contamination (Costa and Duarte, 2017).

Waste management practices

In laboratory environments, efficient waste management, such as separating plastic waste from non-plastic materials, establishing recycling initiatives for plastic products, and embracing sustainable options over single-use plastics whenever possible, can reduce the dissemination of microplastics and mitigate negative environmental effects. (Thareja and Thareja, 2019; Sarkar et al. 2022). Implementing a routine cleaning for laboratory surfaces and equipment utilizing suitable solvents (like 70% ethanol) can assist in mitigating the accumulation of dust and potential sources of contamination (Jones et al. 2024).

Laboratory environmental monitoring

Regular monitoring of laboratory facilities for environmental factors, such as air and water quality, aids in addressing microplastic pollution. Implementation of filtration systems (Tiernan et al. 2022) and water treatment technologies can reduce the levels of airborne and waterborne microplastics in laboratories, lowering the risk of contamination (Schymanski et al. 2021). The use of clean-air equipment, such as biosafety cabinets, can substantially mitigate airborne microfiber contamination. One study reported a 96.5% decrease in contamination levels when samples were processed in a controlled environment. Rigorous protocols for controlling airborne contamination have demonstrated effectiveness in mitigating microplastic contamination. For instance, one study documented a substantial decrease in contamination levels, from 3.8% to 1.1%, after implementing more stringent control measures (Paiva et al. 2022).

Standardization in microplastic analysis

Establishing standardized methods in microplastic analysis is essential to ensure the reliability, comparability, and reproducibility of results across diverse research settings and investigations. In the absence of such standardization, it becomes difficult to compare data and draw meaningful insights about the scale and impact of microplastic contamination.

Consistent sampling methods

Defined guidelines should be established for sample collection, this entails defining appropriate sample sizes, collection techniques, and storage conditions to mitigate contamination and preserve the integrity of microplastics during transportation and subsequent analysis. Standardized sampling protocols will help reduce variability in results stemming from differences in collection methods (ISO, 2023; Cui et al. 2022).

Consistent sample preparation techniques

Develop standardized protocols for sample preparation, such as drying, grinding, or sieving, ensuring these processes do not modify the microplastic properties. For example, drying temperatures should be regulated to prevent the thermal degradation of plastics, generally not exceeding 40 °C (ISO, 2023; Cui et al. 2022).

Calibration with reference standards

The use of certified reference materials is crucial to validate analytical methods and ensure accurate quantification of microplastics. These CRMs should include known size, shape, polymer type, and concentration of microplastic particles. These reference materials enable the establishment of reliable recovery efficiencies and the assessment of the performance of analytical techniques employed in microplastic studies (Cui et al. 2022; Masura et al. 2015).

Validation of analytical techniques

Develop standardized validation protocols for commonly used microplastic detection methods, such as microscopy (SEM, fluorescence), spectroscopy (FTIR, Raman), and chromatography (GC-MS, Py-GC-MS). This involves assessing key performance characteristics, including sensitivity, specificity, and reproducibility, as well as determining appropriate detection limits and quantification thresholds (ISO, 2023; Zhao et al. 2020).

Uniform reporting guidelines

Create uniform templates for documenting microplastic data, encompassing the types, sizes, shapes, concentrations, and polymer compositions of detected microplastics. This ensures consistent communication of results, facilitating comparison across different studies (ISO, 2023).

Inclusion of quality control measures

Mandated that researchers include detailed descriptions of quality control procedures, such as blank controls, spike recoveries, and replicate analyses, in their reports. This enhances the transparency and reliability of the data (Ding et al. 2022; Masura et al. 2015).

Laboratory contamination prevention

Establishing standardized best practices for preventing contamination during microplastic analysis is crucial. This includes the use of materials free of microplastics, maintaining clean laboratory environments (Jones et al. 2024), and employing controlled airflow (Paiva et al. 2022). Implementing consistent contamination prevention measures ensures that external sources of microplastics do not compromise microplastic analysis results.

Documentation of contamination sources

Researchers should be encouraged to thoroughly document and report any potential sources of contamination encountered during microplastic analysis. By developing a comprehensive understanding of these contamination risks, the scientific community can collaboratively establish more robust and reliable protocols to effectively minimize contamination in future studies (Masura et al. 2015).

Interlaboratory comparison studies

Regularly conducting interlaboratory comparison studies can help assess the consistency of microplastic analysis methods across different research facilities. These collaborative exercises facilitate the identification of inconsistencies and opportunities for improvement, ultimately contributing to the development of more standardized and reliable analytical approaches for microplastic research (Masura et al. 2015).

Table 1: Standardization in microplastic analysis

Sr. No.	Recommended Standardized Methods	Key strategies	Explanation	References
1.	Consistent Sampling Methods	Clearly defined, standardized guidelines and protocols for MP sample collection should be established	Define appropriate sample sizes, collection techniques, and storage conditions to mitigate MP contamination and preserve the integrity of microplastics during transportation and subsequent analysis.	(ISO, 2023; Cui et al. 2022)
2.	Consistent MP Sample Preparation Techniques	Standardized protocols for MP sample preparation should be developed.	Define standardized protocols for MP sample preparation like sample drying, grinding, sieving, etc. For example, drying temperatures should be regulated to prevent the thermal degradation of plastics, generally not exceeding 40 °C.	(ISO, 2023; Cui et al. 2022)
3.	Calibration with Reference Standards	Standardized and certified reference materials for MPs should be defined.	Defined CRMs should include MP known size, shape, polymer type, and concentration of microplastic particles.	(Cui et al. 2022; Masura et al. 2015)
4.	Validation of Analytical Techniques	Development of standardized validation protocols for commonly used microplastic detection methods.	Standardized reference data should include key performance characteristics, including sensitivity, specificity, and reproducibility, as well as determining appropriate detection limits and quantification thresholds.	(ISO, 2023; Zhao et al. 2020)
5.	Uniform Documenting Guidelines	Standardized reporting guidelines should be established to ensure the consistent communication of results, facilitating comparison across different studies.	Guidelines should have uniform templates for documenting microplastic data, encompassing the types, sizes, shapes, concentrations, and polymer compositions of detected microplastics.	(ISO, 2023)
6.	Inclusion of Quality Control Measures	Detailed descriptions of quality control procedures should be established.	Descriptions of quality control procedures like blank controls, spike recoveries, and replicate analyses can enhance the transparency and reliability of the data.	(Ding et al. 2022; Masura et al. 2015)
7.	Laboratory Contamination Prevention	Establishing standardized best practices for preventing contamination during microplastic analysis is crucial.	Standardized best practices should include the usage of materials free of microplastics, maintaining clean laboratory environments, and employing controlled airflow.	(Jones et al. 2024; Paiva et al. 2022)
8.	Documentation of MP Contamination	Thorough documentation of microplastic encountered by researchers during the analysis should be encouraged.	The scientific community can collaboratively establish more robust and reliable protocols to minimize contamination in future studies effectively.	(Masura et al. 2015)
9.	Interlaboratory Comparison Studies	Interlaboratory comparison studies should be established to assess the	These collaborative exercises facilitate the identification of inconsistencies and opportunities for improvement, ultimately	(Masura et al. 2015)

		consistency of microplastic analysis methods across different research facilities.	contributing to the development of more standardized and reliable analytical approaches for microplastic research.	
10.	Global Collaboration and Standardization Initiatives	Fostering collaborations among researchers, standardization organizations (e.g., ISO, ASTM), and regulatory bodies is essential.	This collaborative effort is essential for establishing a coherent and comprehensive framework to guide microplastic research.	(ISO, 2023; Cui et al. 2022)
11.	Training and Awareness	Education of laboratory personnel about potential contamination sources and effective prevention strategies should be implemented.	Heightening the awareness of contamination risks can promote more meticulous handling of samples and equipment, thereby further mitigating such risks.	(Gheorghe et al. 2024)

Global collaboration and standardization initiatives

Fostering global collaboration among researchers, standardization organizations (e.g., ISO, ASTM), and regulatory bodies is crucial for developing and implementing universally accepted standards for microplastic analysis. This collaborative effort is essential for establishing a coherent and comprehensive framework to guide microplastic research (ISO, 2023; Cui et al. 2022).

Training and awareness

It is crucial to educate laboratory personnel about potential contamination sources and effective prevention strategies. Heightening their awareness of contamination risks can promote more meticulous handling of samples and equipment, thereby further mitigating such risks (Gheorghe et al. 2024).

In conclusion, the persistent issue of microplastic contamination in laboratory environments poses considerable challenges. However, the implementation of rigorous detection and prevention measures, coupled with the standardization of analytical methodologies, can effectively mitigate these challenges. Continuously improving laboratory practices and fostering greater awareness among researchers are essential for enhancing the reliability and credibility of microplastic research.

Conclusions

Summary of findings

Microplastic presence in laboratory settings

This research paper examines the widespread prevalence of microplastic contamination in laboratory environments. Both intentional and unintentional sources lead to the introduction of microplastics through laboratory instruments, supplies, and environmental factors. The findings underscore the critical need to address these sources to maintain the integrity of experimental research.

Impact on cellular health and research

This paper demonstrates that microplastics can significantly impact cellular health, altering cellular processes and potentially compromising experimental results. These implications extend beyond individual studies, potentially influencing broader research outcomes and leading to misinterpretations if not properly accounted for.

Challenges and strategies

The analysis of the challenges in detecting microplastics highlights the limitations of current methodologies. This study identifies key strategies for preventing contamination and discusses the necessity of standardized protocols to ensure consistent and reliable analysis across laboratories. Improving detection technologies and establishing standardized practices are identified as critical steps in mitigating the impact of microplastics on laboratory research.

Broader implications

Impact on research reliability: The presence of microplastics in laboratory settings raises concerns about the reliability and reproducibility of scientific research. By addressing these issues, this paper contributes to a growing awareness of the need for rigorous contamination control measures in the scientific community.

Relevance to environmental and biomedical fields

The insights gained from this study are relevant not only to laboratory research but also to environmental science and biomedical research. Understanding microplastic contamination at the cellular level helps bridge the gap between environmental exposure and its effects on human health, providing a more comprehensive understanding of microplastic pollution.

Future recommendations

Development of advanced detection methods

Innovative technologies: Future research should focus on developing and improving advanced detection methods that can accurately identify and quantify microplastics at even smaller sizes and lower concentrations. This includes enhancing the sensitivity of current techniques and exploring innovative approaches like microfluidics, lab-on-a-chip devices, and nanoscale imaging.

Standardized reference materials

There is a need for the creation and widespread adoption of standardized reference materials for microplastic analysis. Future research should aim to produce these materials and establish guidelines for their use in the calibration and validation of analytical instruments.

Understanding the long-term effects of microplastics on cellular health

In-Depth toxicological studies: More comprehensive toxicological studies are needed to fully understand the long-term effects of microplastics on cellular health. This includes exploring how chronic exposure to different types and concentrations of microplastics affects cellular functions, gene expression, and overall cell viability.

Implications for human health

Research should also expand to investigate the implications of microplastic contamination in laboratory settings for human health, particularly in medical research and drug development, where microplastics could influence experimental outcomes.

Implementation of contamination control measures

Best Practices and Guidelines: Future studies should work towards the development of detailed best practices and contamination control guidelines specific to different types of laboratories. This includes creating microplastic-free protocols and designing lab environments that minimize the risk of contamination. Emphasizing the importance of education and training in contamination control for laboratory personnel is also crucial.

Interdisciplinary collaboration

Fostering interdisciplinary collaboration: Encouraging collaboration between environmental scientists, toxicologists, chemists, and biomedical researchers can lead to a more holistic understanding of microplastic contamination. Interdisciplinary studies can address the issue from multiple angles, combining expertise to develop comprehensive solutions.

Global standardization efforts

There is a need for coordinated global efforts to standardize microplastic analysis. Researchers should collaborate with international organizations to develop universally accepted standards and protocols, ensuring that findings are comparable across different regions and disciplines.

This paper has highlighted the pervasive challenge of microplastic contamination within laboratory settings, which poses significant threats to the integrity and reliability of scientific research. The findings emphasize the urgent need for the scientific community to prioritize addressing this issue through the development of advanced detection methods, rigorous contamination control strategies, and standardized protocols. While progress has been made, ongoing research and interdisciplinary collaboration will be essential in mitigating the far-reaching impacts of microplastic contamination on both environmental and biomedical fields. This paper serves as a call to action, urging researchers to recognize microplastic contamination as a critical area of study and to continue advancing our collective understanding of its consequences, to ensure the reliability and sustainability of future scientific endeavors.

Abbreviations

BSR	Broad-spectrum resistance
DAMPs	Damage-associated molecular patterns
ETI	Effector-triggered immunity
GLS	Gray leaf spot
NCLB	Northern corn leaf blight
NLRs	Nucleotide-binding leucine-rice proteins
PAMPs	Pathogen-associated molecular patterns
PRRs	Pattern recognition receptors
PTI	Pattern-triggered immunity
QDR	Quantitative disease resistance
QTLs	Quantitative trait loci
RLK	Receptor like kinase
ROS	Reactive oxygen species
Vd	*Verticillium dahlia*
WAKs	Wall-associated receptor-like kinases
Xoo	*Xanthomonas oryzae*

Declarations

Ethics approval
Not applicable.

Consent to participate
Not applicable.

Consent for publication
Not applicable

Conflict of interest
Author declares no conflict of interest.

Acknowledgements
This study was supported by Riphah International University, Faisalabad Campus, Department of Zoology.

Funding
Not applicable.

Data availability
All the data generated are available in the manuscript.

Authors contribution
M.R conceived the study, I., A.N., and I.A. collected the data and wrote the original manuscript, and revised the manuscript. All authors approved the manuscript for publication.

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