



Public perceptions and support for microbiome engineering to combat mold growth in disaster relief efforts

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Abstract

Mold contamination poses persistent challenges in disaster relief shelters, where moisture, limited ventilation, and dense occupancy create conditions favorable for rapid fungal growth. Traditional prevention measures, such as chemical treatments and mechanical drying, often face logistical and resource limitations. Microbiome engineering has been proposed as a novel intervention, yet little is known about public perceptions of such an approach. This study presents the first empirical analysis of attitudes toward introduced microbiomes (IM) in the context of emergency housing. Using a nationally representative survey of 1,000 U.S. adults, we examined demographic, informational, emotional, and risk-related predictors of support across three dimensions: willingness to adopt IM in shelters, support for rigorous evaluation and testing, and support for survivor education. Hierarchical regression models explained 55.7% of variance in adoption, 27.4% in testing, and 21.4% in education support. Findings reveal that adoption support was driven by efficacy beliefs, trust, and affective responses; testing support was shaped by demographic factors and secondary risk concerns; and education support reflected demographic variation and threat appraisals. Across all models, interest in learning more about microbiome engineering consistently predicted higher support, while prior information-seeking often predicted greater caution. These results underscore the importance of integrating public perspectives alongside technical assessments when evaluating microbiome engineering for disaster relief.

Keywords Disaster relief shelters · Mold prevention · Introduced microbiomes · Microbiome engineering · Public perceptions · Risk perception · Responsible research and innovation (RRI)

1 Introduction

Disaster relief operations must balance the urgent need for shelter with the imperative to safeguard health in high-risk environments (UNHCR, 2025). Temporary structures, such as tents, modular units, and other improvised shelters, are indispensable in the aftermath of hurricanes, floods, wildfires, and other large-scale emergencies (Conzatti et al. 2022). However, these environments often foster mold growth, particularly when high humidity, water intrusion, and limited ventilation are present. Mold contamination in emergency shelters is more than an inconvenience; it is a

serious public health concern. Exposure is associated with respiratory illness, allergic reactions, and exacerbation of asthma and other chronic conditions, with vulnerable populations, such as children, older adults, and individuals with preexisting health issues, facing heightened risks (Institute of Medicine 2004).

Current mold prevention methods in disaster contexts rely heavily on chemical fungicides, desiccants, or mechanical ventilation (CDC, 2014). These interventions often face logistical challenges, including the need for repeated application, limited access to power or resources, and the potential for chemical exposure risks. As climate change increases the frequency and severity of disasters, the shortcomings of these approaches underscore the need for more sustainable and effective mold mitigation strategies that can be deployed rapidly and at scale (IPCC, 2022).

Most literature has focused on physical and chemical methods for engineering the indoor environment to reduce harmful fungi in indoor environments like *Aspergillus* and

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Penicillium (Dai et al., 2017). For example, removal of fungi by air filtration has been proposed, as well as reducing humidity and increasing ventilation. Moreover, there have been suggestions that it may be desirable to increase the airborne microbial load in the built environment for a “probiotic” effect (Dai et al., 2017). Yet, the literature on specific approaches to microbiome engineering using the probiotic option in buildings to reduce fungal mold is scarce. The intentional design or modification of microbial communities to reduce fungi that cause disease could improve environmental health outcomes. The authors are part of an NSF-funded center that is exploring probiotic and other microbiome engineering approaches to reduce pathogenic fungi in households. Options being considered by the research teams include bioengineered or “naturally occurring” mycoviruses to attack pathogenic fungi (perhaps deployed by HVAC systems in homes or coated on surfaces in emergency shelters) or other non-pathogenic microbes to outcompete fungi on surfaces or in airborne particles. The technologies are in their infancy, which is a prime time to study public perceptions in order to anticipate the hopes, concerns, and attitudes of the publics who would occupy these built environments. For disaster relief shelters, the introduction of beneficial microbiomes into construction materials offers a novel method to suppress mold growth without the need for continuous maintenance. This microbiome engineering strategy, hereafter referred to as introduced microbiomes (IM), has the potential to improve living conditions in emergency contexts while reducing reliance on chemical interventions. Despite its technical promise, the implementation of IM in disaster shelters depends on public understanding, trust, and acceptance. Emerging technologies in health and environmental contexts often encounter skepticism, driven by perceptions of risk, uncertainty about long-term effects, and concerns over unintended consequences. Understanding these perceptions before these technologies are deployed, and even early in their development, is particularly important in post-disaster settings, where affected populations may already be in a state of heightened vulnerability and mistrust. As terminology in this domain varies across scientific, policy, and public discussions, we clarify the language used throughout this paper. The term ‘microbiome engineering’ refers broadly to the intentional design or introduction of microbial communities to achieve functional outcomes such as mold suppression. Earlier in the manuscript we describe candidate approaches using the term ‘bioengineered,’ which is often used as a general descriptor in both scientific and public communication to denote biologically modified agents without specifying the degree of genetic manipulation involved. In contrast, the term ‘synthetic biology,’ which appears later in the Discussion, refers more specifically to the use of engineering principles to

design or redesign biological systems. To avoid introducing value-laden or politically charged terminology, participants in this study were only exposed to the terms ‘microbiome engineering’ and ‘introduced microbiomes,’ not ‘synthetic biology.’ This clarification ensures consistency between the manuscript narrative and the terminology used in the study instrument.

This study assesses public perceptions of using introduced microbiomes in emergency shelter materials to prevent mold growth. Building on prior research on microbiome engineering in built environments, we evaluate the influence of demographic characteristics, prior engagement with microbiome-related information, emotional responses, and risk appraisals on support for this technology. Specifically, we examine three dimensions of support: (1) willingness to adopt IM in disaster shelters, (2) support for rigorous evaluation and testing prior to deployment, and (3) support for educating disaster survivors about the intervention. Findings from this work can inform disaster relief policy, technology adoption strategies, and risk communication approaches for emerging microbial interventions in public health-sensitive environments.

2 Literature review

IM for mold-resistant shelters represent a proposed intervention that has not yet been implemented in real-world disaster contexts, meaning no empirical research has directly examined public perceptions of this specific application. As the first study to address this gap, our analysis requires building a conceptual foundation from adjacent literature that speak to the technical, social, and governance dimensions of mold control and biotechnology. We begin with research on mold growth in emergency temporary structures, which outlines the environmental conditions that accelerate fungal colonization, the vulnerabilities of commonly used shelter materials, and the logistical barriers to effective mitigation in post-disaster contexts. We then consider work on material degradation and health risks from mold contamination, which documents how fungal activity undermines both the structural performance of shelters and the health of occupants. Next, we review current mold interventions, focusing on the strengths and limitations of existing approaches to prevention and remediation, including chemical treatment, drying, and ventilation, and noting where these measures prove inadequate under emergency conditions. Finally, we examine research on public perceptions of biotechnology and responsible innovation, which provides insight into the factors shaping acceptance, trust, and risk perception in other technological domains and offers governance frameworks relevant for IM. Together, these literatures establish

the scope of the problem, highlight the limitations of existing solutions, and underscore the absence of public perception research on IM in disaster relief shelters. Against this backdrop, the present study investigates how demographic, informational, emotional, and risk-related factors shape public support across three dimensions: adoption of IM in shelters, support for rigorous evaluation and testing, and support for survivor education.

2.1 Mold growth in emergency temporary structures

Emergency shelters deployed in disaster relief operations are often exposed to environmental conditions that favor rapid mold colonization. After wetting, mold can establish within 24 to 48 hours if materials are not thoroughly dried, a timeline consistently reflected in guidance from the U.S. Environmental Protection Agency and FEMA (EPA, 2024; FEMA, 2021). Moisture availability is the critical driver of growth, since most temporary shelter materials, such as plywood, fabrics, insulation, and paper-faced boards, provide sufficient nutrients for mold growth once damp (EPA, 2024). Field realities further compound moisture loading. Site selection on saturated ground, limited ground vapor control, and low platform elevations can allow capillary rise and soil moisture to migrate into floors and wall assemblies. Tight construction without mechanical conditioning increases interior humidity from occupant respiration and cooking, which elevates surface relative humidity and condensation risk, particularly during cool nights (UNHCR, 2025). Natural ventilation, including cross-ventilation through operable openings and stack-driven airflow, plays an important role in temporary shelter performance, especially in settings where electricity for mechanical ventilation is unavailable.

Fig. 1 Mold contamination in temporary shelters (as reported by Watanabe et al. 2021)



Humanitarian shelter guidance emphasizes incorporating passive ventilation features into lightweight structures, although their effectiveness is constrained by ambient humidity, crowding, and the thermal characteristics of temporary building materials (Conzatti et al. 2022; UNHCR, 2025). These passive strategies can reduce moisture accumulation but often cannot maintain sufficiently low humidity during prolonged wet or stagnant-weather conditions, underscoring the need for complementary mold-prevention approaches. For instance, a field investigation following the 2011 Great East Japan Earthquake documented significant mold growth in prefabricated temporary housing units in Miyagi Prefecture within the first summer after occupancy (Watanabe et al. 2021). Surveys found that 84 percent of inspected units had visible mold, with growth concentrated on ceilings, wall corners, and behind furniture. Contributing factors included high interior humidity from occupant activities, inadequate ventilation, and the thermal bridging of lightweight panel walls, which created cool surfaces conducive to condensation. The study highlighted that even newly constructed temporary units, if not designed and managed for moisture control, can experience rapid fungal colonization in humid climates, underscoring the urgency of integrating mold-prevention measures into shelter design and material selection (Hayashi 2015). Figure 1 below shows the significant mold growth in these temporary shelters.

The relationship between temperature and relative humidity means that even when the ambient air appears dry, cold surfaces can maintain a micro-climate at or above the approximate mold threshold of 70 percent relative humidity, supporting spore germination (Building Science Corporation 2002). Surfaces that are several degrees cooler than the room air, such as those at thermal bridges and poorly insulated elements typical of temporary shelters, are particularly



vulnerable. ASHRAE position guidance reinforces the importance of controlling liquid water, humidity, and condensation pathways to limit indoor dampness (ASHRAE, 2021). Many shelter components are not selected or tested for fungal resistance. Standards such as ASTM D3273 assess the relative resistance of interior coatings to mold growth under controlled high-humidity conditions (ASTM International 2021). While these laboratory tests do not directly predict field performance, they can inform procurement decisions for coated fabrics, interior paints, and panel finishes used in temporary units (ANSI 2025). Water-damage restoration standards, such as ANSI/IICRC S500, emphasize the need for rapid drying, dehumidification, and, when necessary, the removal of porous materials that cannot be dried in time (IICRC, 2024). These practices are difficult to execute at scale in emergency contexts, which contributes to persistent mold problems in temporary housing.

Disaster-housing guidance notes that ventilation upgrades and moisture control can improve indoor conditions in transportable and alternative housing units, yet these measures are frequently limited by weather, power availability, and the urgency of deployment (FEMA, n.d.; CDC, 2008). Reports from post-disaster programs have documented recurrent observations of visible mold, underscoring the challenge of maintaining low-moisture conditions in occupied temporary units (FEMA, n.d.; CDC, 2008). The literature therefore indicates that mold risk in emergency shelters arises from the convergence of wet substrates, high interior humidity, cool surfaces that push local relative humidity to critical thresholds, and logistical barriers to rapid drying and ventilation (EPA, 2024). This context underscores the need to explore low-maintenance, materials-embedded strategies that could suppress mold colonization during the critical first days and weeks of shelter deployment.

2.2 Material degradation and health risks from mold contamination

Mold growth in built environments poses significant risks to both structural materials and human health, which is particularly problematic in temporary shelters used for disaster relief. Fungi degrade organic building components—including plywood, oriented strand board, gypsum board, textiles, and certain insulation types—by producing enzymes that break down cellulose and other polymers, weakening the affected materials and potentially impairing their load-bearing capacity over time (Nielsen 2001; Kazemian et al. 2019). Research demonstrates that mold colonization accelerates deterioration of gypsum-based materials, especially in older buildings or those with high humidity exposure (Kazemian et al. 2019). Because the replacement of degraded materials in austere, post-disaster environments is often logistically

complex, these losses can compromise shelter integrity and increase operational burdens. Moreover, surface-coated or “moisture-resistant” materials are not immune to mold damage. If the surface film is compromised or moisture persists long enough to penetrate beneath, mold can colonize interior layers of the panel or board, calling into question the long-term efficacy of such protective treatments.

In addition to material impacts, mold exposure poses recognized health concerns. Fungal spores, fragments, mycotoxins, and microbial volatile organic compounds (MVOCs) are inhalable and can provoke allergic reactions, respiratory inflammation, and other symptoms. Epidemiological evidence links damp and moldy environments with increased incidence of asthma, allergic rhinitis, and hypersensitivity pneumonitis (Institute of Medicine 2004; Khan, 2012). Reviews have also highlighted acute symptoms such as mucous membrane irritation, coughing, wheezing, and fatigue among occupants of mold-contaminated indoor spaces (Bush et al. 2006 Feb).

Although the health risks associated with inhalation of mycotoxins in typical indoor environments remain under investigation, animal studies and selected human exposure cases suggest potential for inflammatory and immunotoxic effects from high-level or prolonged exposure (Robbins et al. 2000; Lindemann et al. 2022). Notably, the threshold of exposure necessary to elicit measurable health outcomes in most non-agricultural indoor settings remains unclear, but active mold growth is broadly considered unsanitary and in need of remediation (Robbins et al. 2000; Institute of Medicine 2004; Lindemann et al. 2022). In disaster relief shelters, conditions often include dense occupancy, limited ventilation, and sustained moisture. These factors create a synergistic environment for both material degradation and elevated human exposure. Together, the combined material and health impacts justify the need for proactive, durable interventions—such as materials embedded with antifungal agents or bioengineering methods—that can suppress mold growth during critical early deployment periods.

2.3 Mold interventions

Current strategies to prevent and remediate mold growth in post-disaster settings rely primarily on moisture control, environmental management, chemical treatment, and worker protection which face significant operational constraints in emergency contexts. The most fundamental prevention strategy is rapid water removal and thorough drying of wet surfaces within 24 to 48 hours to inhibit mold germination (CDC, 2014; Johanning et al., 2014). Dehumidification, enhanced ventilation, air movement via portable fans, and direct sunlight exposure are standard approaches, yet these measures are often impractical or unavailable in

remote or resource-limited disaster zones (Yale University EHS, 2016). Cleaning and remediation typically involve physical removal of mold-laden materials, such as soaked drywall or carpeting, followed by disinfection using solutions such as bleach or biocides and HEPA-filtered vacuuming of spores (CDC, 2014; NIEHS, 2013). Protective equipment such as N95 masks, gloves, and eye protection is recommended for cleanup crews, but in practice may not always be available or properly used, increasing risk for both responders and occupants (NIEHS, 2013).

Public health agencies emphasize source control, such as repairing leaks, reducing indoor humidity, and maintaining adequate drainage and encourage behaviors to minimize exposure, while clinical guidance recommends surveillance and evaluation for mold-related illness following disasters (CDC, 2014). However, accurately assessing environmental mold levels and linking them to health outcomes remains difficult, as mold exposure varies with environmental conditions, individual susceptibility, and cleaning practices (CDC, 2014). At the policy level, programs like HUD's Healthy Homes initiative have promoted moisture control strategies and interventions aimed at preventing mold in residential environments, including demonstration projects and public outreach campaigns. Yet in disaster relief settings, these programs' applicability is limited by the need for rapid deployment and the often-temporary nature of shelters (HUD, 2005). Similarly, shelter design reviews highlight that while improving indoor air quality and ventilation is valuable, clear evidence linking specific design attributes to mold outcomes remains limited, especially in urgent, short-term housing solutions (Conzatti et al. 2022). Moreover, current approaches often treat mold as a symptom rather than integrating prevention into shelter design or materials. The logistical burden of drying, maintenance, and replacement in resource-poor settings means that shelters remain vulnerable to mold despite best-practice interventions—particularly given the high humidity and irregular maintenance typical of disaster response zones (Johanning et al., 2014; Yale University EHS, 2016).

These limitations underscore potential need for improved low-maintenance strategies. One alternative currently being researched is the potential use of IM, microbial communities pre-applied to shelter materials that may inhibit mold formation. As mentioned earlier, bioengineered or naturally occurring mycoviruses (or other “probiotic” microbes that outcompete fungi) could be sprayed on surfaces or could be aerosolized to attack fungi. IM could potentially suppress fungal colonization from deployment onward without requiring active moisture control or chemical treatment, offering a passive, sustainable, and scalable solution in disaster relief contexts where operational capacity is constrained.

Recent research further highlights how indoor microbiomes interact with building materials, ventilation patterns, and occupant behavior, shaping both environmental quality and health outcomes (Gilbert & Stephens, 2018). Parallel innovations in bio-based or biologically active building materials further illustrate a broader movement toward biologically informed design (Bourbia et al. 2023). These developments establish a continuum from passive biological processes to intentional microbiome engineering, positioning IM as one extension of emerging microbiome-aware approaches to building science.

2.4 Public perceptions of biotechnology and responsible innovation

Public perceptions and acceptance play a decisive role in determining whether novel biotechnological interventions achieve successful adoption, especially in contexts where deployment occurs in publicly accessible or highly visible settings. Research across domains consistently shows that public perceptions are shaped by a complex interplay of familiarity, perceived risks and benefits, trust in responsible actors, and ethical or value-based considerations (Cummings, Landreville, & Kuzma, 2025a; Cummings et al. 2024). These influences extend across applications ranging from environmental remediation and agriculture to healthcare and manufacturing, underscoring that while specific technologies may differ, the processes through which the public forms judgments share common patterns (Savadori et al. 2010).

Familiarity can influence acceptance in ways that are not always linear or predictable. Limited public knowledge often leads individuals to rely on heuristics, such as trust in experts or alignment with perceived societal norms, when evaluating a new intervention (Hardwick et al. 2024). In some cases, increasing familiarity through early engagement and targeted communication can build support if messages emphasize relevance, clear benefits, and safety, as was the case for public acceptance of second-generation biofuels (Dragojlovic & Einsiedel, 2014). Conversely, familiarity can lead to skepticism if information frames highlight uncertainties, risks, or contested applications. How a biotechnology is characterized—whether as innovative, natural, sustainable, or conversely as artificial, risky, or disruptive—can significantly influence perceptions.

Trust in implementing organizations, regulatory bodies, and scientific institutions remains a pivotal determinant of acceptance. High trust is associated with greater openness to novel biotechnologies, while low trust can magnify perceived hazards and slow adoption (Siegrist 2000; Connor & Siegrist 2015). In a recent study by this authorship team, we found that trust in institutional efficacy was a pivotal factor

shaping public support for use of microbiome engineering in hospital settings to combat hospital-acquired infections and antimicrobial resistance (Cummings et al. 2025b). Trust-building requires transparent governance, credible demonstration of benefits, and engagement processes that meaningfully address public concerns. The perceived controllability, reversibility, and value alignment of an intervention also shape whether it is supported or resisted (Gaskell et al., 2011).

Responsible Research and Innovation (RRI) frameworks provide a structured approach to embedding these trust-building practices within the innovation process. RRI emphasizes anticipation, reflexivity, inclusion, and responsiveness—principles that seek to align technological development with societal needs and values (Owen et al. 2012; Stilgoe et al. 2013). Anticipation involves considering potential impacts, risks, and unintended consequences before deployment. Reflexivity calls on innovators to critically assess their assumptions and decision-making processes. Inclusion ensures that diverse stakeholder perspectives are engaged early and often, while responsiveness demands that projects adapt to stakeholder feedback and evolving societal priorities.

Risk–benefit evaluations remain central to public judgments. When perceived benefits—such as environmental protection, improved safety, or increased resilience—are seen as substantial and urgent, tolerance for uncertainty may increase (Cummings et al. 2024). Conversely, if risks are perceived to outweigh potential advantages, resistance tends to grow, even in cases where technical risk assessments indicate low hazard. Cultural context, political orientation, and prior experiences with related technologies can mediate these judgments (Kahan et al. 2010). Embedding RRI practices into this evaluative process provides an avenue for not only improving understanding but also co-producing solutions that are socially robust. For novel applications, evidence from adjacent fields suggests that early, proactive engagement with stakeholders is critical. This includes providing accessible, balanced information, creating opportunities for dialogue, and demonstrating effectiveness and safety through transparent testing and monitoring. When such approaches are grounded in RRI principles, they can enhance both the perceived legitimacy of the intervention and the likelihood of its sustained adoption.

Despite growing attention to mold contamination in temporary shelters, existing studies have largely focused on material science, health outcomes, or short-term remediation strategies. Far less is known about how the public perceives novel microbial or microbiome-based interventions in disaster relief contexts. Research on public perceptions of biotechnology and microbiome engineering provides important insights, but to date, no empirical work has

examined attitudes toward the use of introduced microbes in emergency shelters. This represents a critical gap, as public support, trust, and acceptance are essential for the responsible deployment of these interventions.

To address this gap, the present study investigates how demographic, informational, emotional, and risk-related factors shape public support for mold-resistant shelters using introduced microbiomes. Specifically, the analysis examines three dimensions of support: willingness to adopt such shelters, support for rigorous evaluation and testing, and support for education of disaster survivors. Accordingly, we pose the overarching research question: What factors influence public support for the use of introduced microbiomes in mold-resistant disaster relief shelters? See Fig 1 for a conceptual diagram of our proposed model.

3 Method

This investigation employed a cross-sectional survey design to assess public perceptions of microbiome engineering within the built environment. Data were collected in December 2023 from 1000 U.S. adults (aged 18 and older), constituting a nationally representative sample. This sample was drawn from YouGov’s National Omnibus Panel. The survey results possess a margin of error of ± 3.38 percentage points.

3.1 Sample characteristics

The sample comprised 480 men, 510 women, 4 non-binary/genderqueer individuals, and 5 transgender respondents. Additionally, 2 participants did not disclose their gender, and 1 person identified as “no label.” The participants’ average age was 49 years ($SD = 17.71$), with a range of 19 to 88 years. The racial composition of the sample was predominantly White (64.7%), followed by Hispanic or Latino (14.8%), and Black or African American (12.1%). Smaller percentages included Asian (3.3%), and those identifying as Native American, Middle Eastern, or other racial/ethnic backgrounds (5.1%). In terms of urban-rural classification, the vast majority (85.1%) of participants resided in metropolitan areas (central counties with at least 50,000 urban residents), while 14.8% lived in non-metro regions (areas with fewer than 50,000 people). Educational attainment was mixed: 346 respondents (roughly one-third of the sample) had a four-year college degree or higher, while 654 participants had not completed a four-year degree. Income distribution saw 267 lower-income participants (earning less than \$30,000 annually), 443 middle-income participants (earning \$30,000–\$99,999 per year), and 290 higher-income participants (earning \$100,000 or more annually).

3.2 Survey procedures

Respondents first addressed inquiries concerning their general science and technology beliefs (these items were excluded from the present analysis). They were then provided a concise explanation of microbiome engineering in the built environment (refer to Supplemental Materials), followed by questions assessing their general perceptions of microbiome engineering. Subsequently, the participants were instructed to review the ensuing account detailing a possible application of microbiome engineering: “In disaster relief efforts, providing shelter for displaced individuals is very important. Traditional temporary structures, such as tents and makeshift shelters, often lack the necessary safeguards against mold growth, which can pose severe health risks in the wake of disasters such as flooding. Introduced microbiomes offer an innovative solution to address this pressing need by creating mold-resistant emergency shelter structures.” After reading the description, participants offered responses regarding their attitudes toward employing introduced microbes in emergency shelters to inhibit mold Fig 2.

3.3 Independent variables

In addition to demographic and sociographic factors, the study included independent variables previously linked to support for microbiome engineering in the built environment (Cummings et al. 2024, 2025a). Political orientation

was measured on a 7-point party ID scale (1 = strong Democrat, 7 = strong Republican; $M = 3.82, SD = 2.21$). Religious attendance ranged from 1 (‘rarely attends’) to 6 (‘attends weekly’), $M = 2.78, SD = 1.77$.

Microbiome engineering (ME) knowledge was measured with two variables: familiarity with ME (an average of three items, $M = 2.57, SD = .96, \alpha = .83$) and perceived knowledge of ME (an average of four items ($M = 2.71, SD = .92, \alpha = .84$)). Information engagement with ME was measured with two variables: desire to learn more about ME (assessed with one item, $M = 3.59, SD = 1.07$) and prior information-seeking about ME (measured with one question, $M = 2.25, SD = 1.10$). Full item wording is available in the Supplemental Materials.

Emotions about ME were included as predictors. After reading the initial description, participants rated seven negative and seven positive emotions on a 1–5 scale. Negative emotions (disgust, distaste, anger, fear, anxiety, helplessness, nervousness) were averaged into a composite ($M = 1.96, SD = .90, \alpha = .92$), as were positive emotions (excitement, satisfaction, relief, enthusiasm, optimism, wonder, contentment; $M = 2.49, SD = .92, \alpha = .91$).

Threat and coping appraisals were also included as independent variables. Threat appraisal of mold in emergency shelters was measured by susceptibility ($M = 3.61, SD = .91$) and severity ($M = 3.96, SD = .72$), of which severity was based on two items, $r(1,000) = .341, p < .001$. Coping appraisal of introduced microbes (IM) included response efficacy ($M = 3.36, SD = .97$) and trust in relief organizations

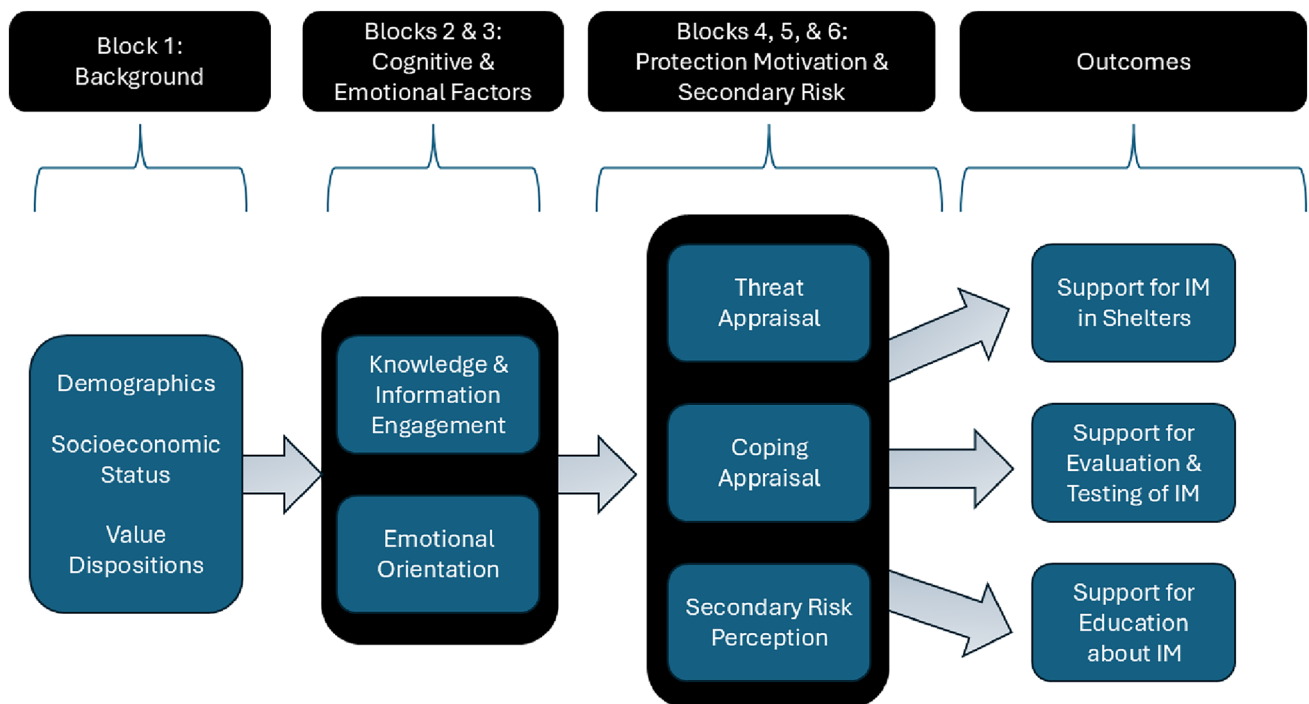


Fig. 2 Conceptual diagram of our proposed model.

and regulatory agencies to provide safe-use guidelines ($M = 3.22$, $SD = 1.08$).

A final predictor was secondary risk perception of IM-based shelter materials, measured with one item addressing concerns about unintended effects on indoor air quality or health in emergencies ($M = 3.63$, $SD = .92$).

3.4 Dependent variables

Three dependent variables addressed the study's research question. Model 1—support for IM-based mold-resistant shelters—was the average of two items ($M = 3.67$, $SD = .87$, $r(1,000) = .683$, $p < .001$). Model 2—support for rigorous testing—was measured with one item ($M = 4.10$, $SD = .88$). Model 3—support for educating disaster survivors—was also measured with one item ($M = 3.99$, $SD = .84$). Full item wording is available in the Supplemental Materials.

3.5 Analytic approach

To examine factors influencing public support for introduced microbiomes (IM) in shelter materials, we conducted hierarchical OLS regression analyses. This approach assessed the incremental impact of predictor blocks, which were entered to reflect presumed causal order. Block 1 included demographics, political orientation, and religious attendance—capturing values and worldview. Block 2 added ME knowledge (familiarity and perceived knowledge) and ME information engagement (desire to learn more and information seeking). Block 3 introduced emotional responses (positive and negative), given their influence on risk perception. Block 4 assessed threat appraisal (perceived severity and susceptibility of mold exposure). Block 5 included coping appraisal (belief in IM efficacy and trust in institutions). Block 6 added secondary risk perception regarding unintended consequences of IM. This structure allowed for a nuanced understanding of psychological, social, and informational drivers of support.

4 Results

This study examined predictors of public support for introduced microbiomes (IM) across three dimensions: (1) willingness to adopt IM for mold-resistant disaster relief shelters, (2) support for rigorous evaluation and testing of IM prior to deployment, and (3) support for educating disaster survivors about IM use. Table 1 presents the hierarchical regression models for each dependent variable, showing the incremental contribution of demographic, informational, emotional, and risk-related predictors. Figure 3 presents a graphical representation of the results.

Regarding support for use of IM in emergency shelters in Model 1, the final model explained 55.7% of the variance in support for adopting IM in shelters, the highest explanatory power among the three outcomes. Demographic factors (Block 1) accounted for 7.1% of the variance. Political orientation emerged as the strongest demographic predictor, with more Republican respondents significantly less supportive of IM ($\beta = -.229$, $p < .001$). Higher educational attainment was also positively associated with support ($\beta = .079$, $p = .020$), while other demographic characteristics such as age, sex, and income were not significant in the final model. General attitudes and behaviors toward microbiome engineering (Block 2) contributed an additional 17.2% of explained variance. The strongest single predictor in the entire model was the desire to learn more about microbiome engineering ($\beta = .419$, $p < .001$). Interestingly, prior information-seeking about microbiomes was negatively associated with adoption support ($\beta = -.082$, $p = .046$), suggesting that those who actively sought information held more cautious views. Emotional responses toward ME (Block 3) explained another 9.2% of variance. Both negative ($\beta = -.287$, $p < .001$) and positive emotions ($\beta = .234$, $p < .001$) were significant, highlighting that affective reactions played a substantial role in shaping willingness to adopt IM. Threat appraisal variables (Block 4) added 4.6% variance. Both perceived severity of mold in shelters ($\beta = .191$, $p < .001$) and perceived susceptibility to mold ($\beta = .059$, $p = .048$) were positively associated with support. Coping appraisal variables (Block 5) accounted for an additional 17.4% variance. Response efficacy of IM ($\beta = .318$, $p < .001$) and trust in relief organizations and regulatory agencies ($\beta = .268$, $p < .001$) were both strong positive predictors, suggesting that efficacy beliefs and institutional trust are critical drivers of support. Finally, secondary risk perceptions (Block 6) added 2.0% variance. Concerns about unintended consequences of IM on indoor air quality and health were negatively associated with adoption ($\beta = -.049$, $p = .048$). Overall, willingness to support IM adoption in shelters was shaped by a mix of cognitive, emotional, and trust-based predictors. See Figure 3 for a summary of significant predictors.

Model 2 explained 27.4% of the variance for testing support, notably less than adoption support but still substantial. Demographic variables (Block 1) explained 6.4% of the variance. Older respondents were significantly more supportive of testing ($\beta = .149$, $p < .001$). Race was significant, with white respondents more supportive than non-white respondents ($\beta = .089$, $p = .007$). Republican party identification predicted lower support ($\beta = -.086$, $p = .009$). Other demographic variables such as sex, education, and religious attendance were not significant. General attitudes and behaviors toward ME (Block 2) added 9.5% of variance. Desire to learn more about ME strongly predicted

Table 1 Hierarchical regression models for (1) support for introduced microbiomes (IM) to create mold-resistant emergency shelters, (2) support for evaluation of IM, and (3) support for education about IM

Block	Item	Model 1: support for IM in emergency shelters		Model 2: support for rigorous evaluation and testing of IM		Model 3: support for education about IM to disaster survivors	
		Stand. β	p -value	Stand. β	p -value	Stand. β	p -value
<i>1. Demographics, sociographics, and value dispositions</i>							
	Age	-.024	.451	.149	<.001***	.105	.001***
	Biological sex (male coded high)	-.027	.397	-.021	.504	-.070	.029*
	Race (white = 1; nonwhite = 0)	.032	.334	.089	.007**	.067	.043*
	Metro Area Status (metro = 1; nonmetro = 0)	-.027	.401	-.062	.050*	.048	.139
	Highest level of education (1 = four-year college degree; 0 = no college degree)	.079	.020*	.054	.115	-.021	.540
	Annual income (higher income coded high)	.054	.110	.078	.022*	.071	.040*
	Political orientation (Republican coded high)	-.229	<.001***	-.086	.009**	-.127	<.001***
	Religious attendance (more frequent coded high)	.017	.594	-.052	.107	.029	.370
	Block 1 R ² (%)	7.1%***	6.4%***	3.8%***			
<i>2. ME knowledge and ME information engagement</i>							
	Familiarity with ME	.002	.967	-.141	.020*	.025	.685
	Perceived knowledge about ME	.090	.119	.067	.270	-.003	.965
	Desire to learn more about ME	.419	<.001***	.269	<.001***	.263	<.001***
	Prior information-seeking about ME	-.082	.046*	-.171	<.001***	-.125	.005**
	Block 2 R ² change (%)	17.2%***	9.5%***	6.7%***			
<i>3. Emotional orientation toward ME</i>							
	Negative emotion toward ME	-.287	<.001***	-.084	.009**	-.049	.143
	Positive emotion toward ME	.234	<.001***	.030	.439	.017	.662
	Block 3 R ² change (%)	9.2%***	0.6%*	0.2%			
<i>4. Threat appraisal of mold growth in disaster relief shelters</i>							
	Severity (magnitude) perception	.191	<.001***	.239	<.001***	.222	<.001***
	Susceptibility (likelihood) perception	.059	.048*	.007	.827	.088	.011**
	Block 4 R ² change (%)	4.6%	5.4%***	6.8%***			
<i>5. Coping appraisal of IM</i>							
	Response efficacy of IM in emergency shelters	.318	<.001***	.033	.391	.043	.283
	Trust in relief organizations and regulatory agencies to provide clear guidelines for the safe use of IM	.268	<.001***	.063	.106	-.001	.984
	Block 5 R ² change (%)	17.4%***	0.5%	.1%			
<i>6. Secondary risk perception of IM</i>							
	Concerns with unintended consequences of IM on indoor air quality and health	-.049	.048*	.254	<.001***	.218	<.001***
	Block 6 R ² change (%)	2.0%*	5.0%***	3.7%***			
	Total R ² (%)	55.7%***	27.4%***	21.4%***			

The R² change is provided for each set of predictors, and standardized coefficients for the final model are listed. Due to rounding, the individual block R² change may not equal the total R² (%) that is reported at the bottom of the table. * $p < .05$, ** $p < .01$, *** $p < .001$

testing support ($\beta = .269, p < .001$), while prior information-seeking was again negatively associated ($\beta = -.171, p < .001$). Familiarity with ME was also negatively associated ($\beta = -.141, p = .020$), suggesting that greater familiarity may raise caution about testing processes. Emotions toward ME (Block 3) added a marginal 0.6% variance. Negative emotions were weakly but significantly associated with reduced support ($\beta = -.084, p = .009$), whereas positive emotions did not predict testing support. Threat appraisal (Block 4) added 5.4% variance. Perceived severity of mold ($\beta = .239,$

$p < .001$) was a strong positive predictor, while perceived susceptibility was nonsignificant. Coping appraisal (Block 5) contributed little additional explanatory power (0.5%). Neither response efficacy nor trust in organizations was a significant predictor of testing support in the final model. Secondary risk perceptions (Block 6) added 5.0% variance. Concerns with unintended consequences of IM strongly predicted higher support for testing ($\beta = .254, p < .001$), consistent with the interpretation that perceived risk motivates stronger demands for evaluation safeguards. Together,

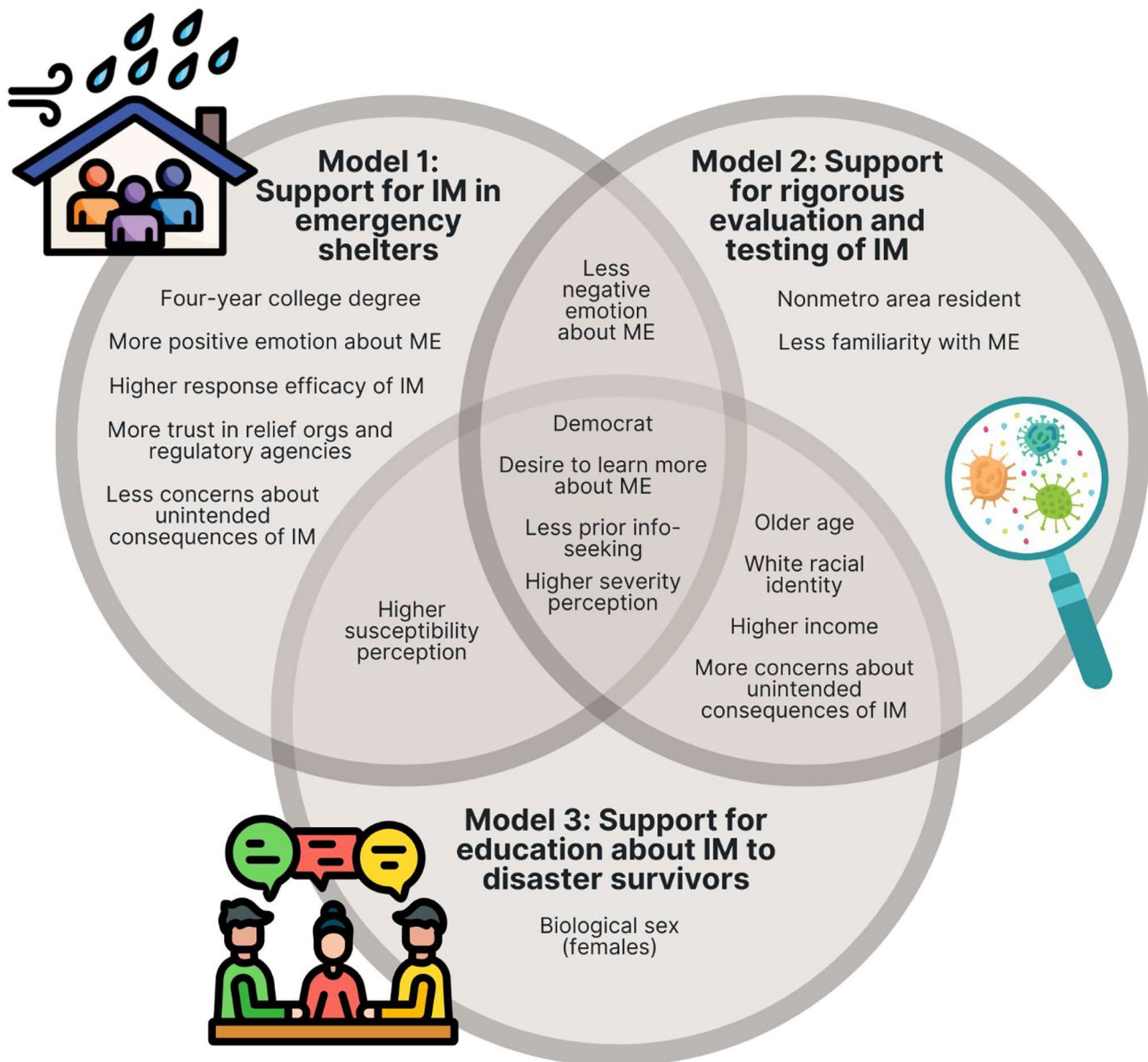


Figure 3. The venn diagram shows the significant predictors of the three regression models. overlapping areas signify common significant predictors among the respective models.

these findings suggest that support for testing is nearly universal and shaped less by emotional or institutional factors than by demographic differences and risk-related appraisals. Importantly, individuals most concerned about unintended consequences were among the strongest proponents of rigorous testing.

Model 3 explained 21.4% of the variance in support for education about IM to disaster survivors. Demographics (Block 1) explained 3.8% of variance. Older age ($\beta = .105$, $p = .001$), white racial identity ($\beta = .067$, $p = .043$), and higher income ($\beta = .071$, $p = .040$) were significant positive predictors. Male respondents were less supportive than female respondents ($\beta = -.070$, $p = .029$), and Republican

party identity predicted lower support ($\beta = -.127$, $p < .001$). General attitudes and behaviors about ME (Block 2) added 6.7% of variance. Desire to learn more about ME was again a strong positive predictor ($\beta = .263$, $p < .001$). In contrast, prior information-seeking was negatively associated ($\beta = -.125$, $p = .005$). Emotions (Block 3) contributed virtually no additional variance (0.2%). Neither negative nor positive emotions toward ME significantly predicted support for education. Threat appraisal (Block 4) added 6.8% variance. Both perceived severity ($\beta = .222$, $p < .001$) and perceived susceptibility ($\beta = .088$, $p = .011$) significantly predicted higher support, suggesting that individuals who recognize mold as a serious and likely threat also prioritize survivor

education. Coping appraisal (Block 5) explained little variance (0.1%). Neither response efficacy nor trust in organizations predicted support for survivor education in the final model. Secondary risk perceptions (Block 6) added 3.7% variance. Concerns with unintended consequences of IM strongly predicted greater support for survivor education ($\beta = .218, p < .001$). These findings suggest that support for survivor education is broadly endorsed, with risk perceptions and threat appraisals playing key roles. Demographic and socioeconomic factors also shaped attitudes, while emotional responses and trust in organizations were relatively unimportant.

5 Discussion

Across all three models, distinct but complementary patterns emerged in the predictors of public support for introduced microbiomes IM. Support for IM adoption in disaster relief shelters (which maintained support from 70.1% of respondents) was shaped most strongly by affective responses, efficacy beliefs, and institutional trust, producing the highest explanatory power (55.7% of variance explained). In contrast, support for rigorous evaluation and testing—while nearly universal (78.5% of respondents agreed or strongly agreed)—was driven less by emotions or trust and more by demographic characteristics, risk appraisals, and a desire to learn more about microbiome engineering (27.4% of variance explained). Education of disaster survivors received broad support as well (76.6% of respondents supported education efforts), with demographic and socioeconomic predictors (e.g., age, sex, race, and income) interacting with threat and secondary risk perceptions to account for 21.4% of variance. Notably, across all three models, desire to learn more about microbiome engineering consistently predicted stronger support, while prior information-seeking often predicted greater caution, underscoring the dual importance of both information exposure and its framing. Collectively, these findings suggest that adoption, testing, and education reflect overlapping but distinct dimensions of public acceptance, with adoption most influenced by emotional and trust-based factors, testing by perceived risks, and survivor education by demographic variation and threat appraisals.

The findings of this study align closely with the principles of Responsible Research and Innovation (RRI), which emphasize anticipation, reflexivity, inclusion, and responsiveness in the development and deployment of emerging technologies (Owen et al. 2012; Stilgoe et al. 2013). As stated in the introduction, using probiotic or synthetic biology approaches to engineer the built environment microbiome in order to reduce pathogenic fungi is in its infancy. As the authors are part of a larger team

working on the engineering approaches, we are embedding the principles of RRI into the projects initially by a study of public attitudes towards an IM approach. Anticipating public attitudes can help guide the technological development towards more responsible paths. The clear influence of emotional reactions and institutional trust on adoption decisions underscores the need for anticipatory governance that accounts for public affect and perceptions of legitimacy alongside technical risk assessments. RRI's focus on reflexivity is likewise reflected in the importance of secondary risk perceptions, as participants who voiced concerns about unintended consequences nevertheless supported rigorous evaluation and survivor education. This indicates that skepticism does not necessarily translate into rejection, but rather into a demand for safeguards, transparency, and adaptive oversight. Inclusion is also highlighted by the demographic variation observed in rigorous evaluation support (Model 2) and survivor education support (Model 3), with older, higher-income, and white respondents showing stronger endorsement. These patterns suggest that inclusive design and communication strategies should be tailored to address the needs and concerns of different social groups to avoid inequities in the benefits of innovation. Responsiveness is evident in the finding that a desire to learn more about microbiome engineering was consistently one of the strongest predictors of support across all outcomes. This highlights the opportunity for scientists, relief organizations, and regulators to provide accessible, transparent, and ongoing educational initiatives that not only inform but also adapt to public feedback. The negative association between information-seeking and adoption support may reflect the types of narratives and framings that individuals encounter when searching for information about microbiomes or biotechnological interventions. Prior research shows that general information seeking about emerging technologies commonly exposes individuals to precautionary, uncertainty-focused, or risk-amplifying narratives (Scheufele & Lewenstein 2005; Brossard 2013). Further demonstrate that discussions of microbial interventions and genetic engineering frequently foreground concerns about unintended consequences, long-term ecological effects, or insufficient regulatory oversight (Hilgartner 2015). Such framing may increase the salience of risk and can heighten skepticism, particularly when authoritative explanatory materials are less prevalent than sensationalized or cautionary content. Information-seeking may therefore connect individuals to disproportionately risk-oriented sources, helping explain why those who search for information demonstrate lower adoption support.

In practical terms, IM-based materials could be introduced through phased pilot deployments in partnership with humanitarian relief organizations. Such pilots would allow

agencies to assess performance, safety, and operational feasibility under real-world disaster conditions while maintaining alignment with existing shelter-health guidelines. Evaluation frameworks commonly used for environmental health interventions could be adapted to assess IM, ensuring that testing, monitoring, and procurement decisions incorporate both technical efficacy and public acceptance considerations. Integrating IM into these established processes would support responsible adoption and help ensure that emerging microbial technologies complement, rather than replace, existing mold-prevention and shelter-safety practices. Furthermore, as the technology develops, future work should also assess the comparative costs of IM relative to conventional mold-prevention strategies *in situ*.

More broadly, the study demonstrates that effective implementation of IM in disaster relief requires attention to the social as well as the technical dimensions of innovation. Adoption will depend on establishing trust and conveying efficacy, testing will require robust safeguards that address perceived risks, and survivor education must ensure equitable access to knowledge across diverse communities. Together, these findings suggest that IM technologies could be responsibly advanced through participatory governance frameworks, interdisciplinary collaboration, and transparent communication that anticipates both enthusiasm and concern. By embedding these practices into disaster relief planning, the adoption of IM can contribute not only to mold-resistant shelters but also to the strengthening of trust in science and technology during times of crisis.

The findings of this study open several opportunities for advancing both research and practice at the intersection of disaster relief, microbiome innovation, and responsible governance. One opportunity lies in extending the scope of inquiry beyond the general U.S. adult population to include disaster survivors, relief workers, and frontline organizations. These groups bring direct lived experience of emergency housing conditions and could provide insights that complement and deepen survey-based evidence. Another opportunity involves moving from cross-sectional attitudes to behavioral and longitudinal research. While this study examined predictors of stated support, future work could investigate how these attitudes translate into actual behaviors under disaster conditions, and how they evolve over time as new technologies are introduced, tested, and communicated. There are also opportunities to incorporate additional contextual factors that shape public perceptions, such as media narratives, prior disaster experience, and local trust in emergency management institutions. Examining how these dynamics interact with demographic, emotional, and risk-based predictors could generate richer models of public acceptance. Similarly, exploring how different framings of IM—for example, emphasizing naturalness, innovation,

or safety—shape support offers a valuable path for refining communication and engagement strategies. Finally, this work highlights opportunities for cross-national and interdisciplinary collaboration. As this study was conducted in the United States, the findings should not be assumed to generalize directly to other national or regional contexts. Public attitudes toward biotechnology, microbial interventions, and environmental risk mitigation can differ widely across countries due to variations in cultural norms, levels of institutional trust, and regulatory expectations. These differences may indicate that international implementation of IM technologies could require locally grounded engagement and region-specific research. Even so, the present findings provide an early foundation for understanding public perspectives on IM and highlight the value of conducting comparative studies in diverse global settings. Future comparative studies could assess how support varies across cultural and institutional contexts, particularly in regions facing different climate, housing, or disaster vulnerabilities. Deliberative and participatory engagement with affected communities can also provide opportunities to co-design governance approaches consistent with Responsible Research and Innovation (RRI) principles. Interdisciplinary collaborations between social scientists, engineers, microbiologists, and policymakers present further opportunities to align technical efficacy and safety with public trust and social values, ensuring that the development of IM technologies advances responsibly, equitably, and effectively.

6 Conclusion

This study provides the first empirical assessment of public perceptions of IM as a potential intervention to mitigate mold growth in disaster relief shelters. By analyzing three dimensions of support—adoption of IM, rigorous evaluation and testing, and survivor education—the results show that perceptions are influenced by a mix of demographic, informational, emotional, and risk-related factors. Adoption was most associated with efficacy beliefs, trust, and emotional reactions; support for testing was shaped by concerns about unintended consequences and demands for safeguards; and support for survivor education was linked to demographic variation and threat appraisals. These findings extend research on biotechnology perceptions into the relatively unexplored context of disaster relief and built environments. They illustrate that attitudes toward novel interventions are not uniform but instead reflect distinct drivers depending on the dimension of support under consideration. The consistent association between interest in learning more about microbiome engineering and higher support across all outcomes points to the importance of

information-seeking as a marker of engagement, while the association of prior information-seeking with greater caution suggests that the nature and framing of information encountered warrants closer study.

In practical terms, the study highlights the value of integrating social dimensions into assessments of new technologies for disaster response. Responsible Research and Innovation (RRI) principles—anticipation, reflexivity, inclusion, and responsiveness—provide a useful framework for interpreting these results, especially as concerns about unintended consequences and issues of trust surfaced across multiple models. Applying such frameworks may help align technical development with social contexts in which disaster relief interventions are deployed. Overall, this study underscores the importance of examining public perspectives alongside technical evaluations when considering novel microbial approaches to disaster relief housing. By identifying the factors that shape different dimensions of support, it provides an empirical foundation for future interdisciplinary research and governance efforts aimed at ensuring that new interventions are developed and evaluated in ways that are responsible, equitable, and effective.

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Data availability The data supporting the findings of this study may be obtained from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

- ANSI. (2025). ANSI/ASTM D3273-21: Mold resistance of interior coatings. <https://blog.ansi.org/ansi/astm-d3273-21-mold-resistance-interior-coatings/>
- ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2021). Limiting indoor mold and dampness in buildings (Position Document). Retrieved from: <https://www.ashrae.org/File%20Library/About/Position%20Documents/pd-on-limiting-indoor-mold-and-dampness-in-buildings-english.pdf>
- ASTM International. (2021). ASTM D3273-16: Standard test method for resistance to growth of mold on the surface of interior coatings

- in an environmental chamber. <https://www.astm.org/d3273-16.html>
- Bourbia S, Kazeoui H, Belarbi R (2023) A review on recent research on bio-based building materials and their applications. *Mater Renew Sustain Energy* 12:117–139. <https://doi.org/10.1007/s40243-023-00234-7>
- Brossard D (2013) New media landscapes and the science information consumer. *Proc Natl Acad Sci U S A* 110(Suppl. 3):14096–14101. <https://doi.org/10.1073/pnas.1212744110>
- Building Science Corporation. (2002). Relative humidity (Report RR-0203). <https://buildingscience.com/documents/reports/rr-0203-relative-humidity/view>
- Bush RK, Portnoy JM, Saxon A, Terr AI, Wood RA (2006) The medical effects of mold exposure. *J Allergy Clin Immunol* 117(2):326–333. <https://doi.org/10.1016/j.jaci.2005.12.001>
- California Department of Public Health. (2024). Mold information. <https://www.cdph.ca.gov/Programs/cls/dehl/eh/Pages/AQS/Mold.aspx>
- CDC, Centers for Disease Control and Prevention. (2008). CDC releases reports on formaldehyde tests of trailers. https://archive.cdc.gov/www_cdc.gov/media/pressrel/2008/r080702.htm
- CDC, Centers for Disease Control and Prevention. (2014). Mold prevention strategies and possible health effects in the aftermath of hurricanes, floods, and other water-damaged buildings (Publication No. RR-55). <https://www.cdc.gov/mmwr/preview/mmwrhtml/rr5508a1.htm>
- Centers for Disease Control and Prevention, Environmental Protection Agency, Federal Emergency Management Agency, Department of Housing and Urban Development, & National Institutes of Health (2024) Homeowners and renters guide to mold cleanup after disasters (PDF). U.S. Department of Health and Human Services. <https://www.cdc.gov/mold-health/communication-resources/guide-to-mold-cleanup.html>
- Connor M, Siegrist M (2015) The stability of risk and benefit perceptions: a longitudinal study assessing the perception of biotechnology. *J Risk Res* 19(4):461–475. <https://doi.org/10.1080/13669877.2014.988169>
- Conzatti A, Kershaw T, Copping A, Coley D (2022) A review of the impact of shelter design on the health of displaced populations. *J Int Humanitarian Action* 7:18. <https://doi.org/10.1186/s41018-022-00123-0>
- Cummings C, Rosenthal S, Kong WY (2020) Secondary risk theory: validation of a novel model of protection motivation. *Risk Anal*. <https://doi.org/10.1111/risa.13573>
- Cummings C, Landreville KD, Kuzma J (2024) Taking the temperature of the United States public regarding microbiome engineering. *Front Public Health* 12:1477377
- Cummings CL, Landreville KD, Kuzma J (2025b) Public perceptions and support for introduced microbes to combat hospital-acquired infections and antimicrobial resistance. *PLoS ONE* 20(10):e0332578
- Cummings CL, Landreville KD and Kuzma J (2025a). Natural vs. genetically engineered microbiomes: understanding public attitudes for indoor applications and pathways for future engagement. *Front. Genet.* 16:1560601. <https://doi.org/10.3389/fgene.2025.1560601>.
- Dai D, Prussian AJ II, Marr LC, Vikesland PJ, Edwards MA, Pruden A (2017) Factors shaping the human exposome in the built environment: Opportunities for engineering control. *Environ Sci Technol* 51(14):7759–7774. <https://doi.org/10.1021/acs.est.7b01097>
- Department of Environmental Health and Preventive Medicine (2014) Review of health hazards and prevention measures for response and recovery workers and volunteers after natural disasters, flooding, and water damage: mold and dampness. *Environ Health Prev Med* 19:93–99. <https://doi.org/10.1007/s12199-013-0368-0>

- Dragojlovic N, Einsiedel E (2015) What drives public acceptance of second-generation biofuels? Evidence from Canada. *Biomass Bioenerg* 75:201–212. <https://doi.org/10.1016/j.biombioe.2015.02.020>
- EPA, U.S. Environmental Protection Agency. Retrieved from <https://www.epa.gov/mold/mold-course-chapter-4FEMA>. (2021). Fact sheet: Mold: Problems and solutions. <https://www.fema.gov/pres-s-release/20250121/fact-sheet-mold-problems-and-solutions>
- FEMA. (n.d.). A case study of the Mississippi Alternative Housing Program. https://www.fema.gov/pdf/about/programs/ahpp/ahpp_ms_cs.pdf
- Federal Emergency Management Agency (2021). Recovery fact sheet 004: Mold remediation and disaster assistance (DR-4615-NY). <https://www.townofcortlandtyny.gov/documents/supervisor/fema%20recovery%20fact%20sheet%2010.28.2021.pdf>
- Gaskell G, Allansdottir A, Allum N, Castro P, Esmer Y, Fischler C, Jackson J, Kronberger N, Hampel J, Mejlgard N, Quintanilha A, Rammer A, Revuelta G, Stares S, Torgersen H, Wager W (2011) The 2010 Eurobarometer on the life sciences. *Nat Biotechnol* 29(2):113–114. <https://doi.org/10.1038/nbt.1771>
- Gilbert JA, Stephens B (2018) Microbiology of the built environment. *Nat Rev Microbiol* 16(11):661–670. <https://doi.org/10.1038/s41579-018-0065-5>
- Hardwick, A., Cummings, C., Graves Jr, J., & Kuzma, J. (2024). Can societal and ethical implications of precision microbiome engineering be applied to the built environment? *Environment Systems and Decisions*.
- Hayashi K (2015) Health problem caused by mold in mega-disaster. *JSM Mycotoxins* 65(2):103–107. <https://doi.org/10.2520/myco.65.103>
- Hilgartner S (2015) Capturing the imaginary: Vanguards, visions, and the synthetic biology revolution. In: Hilgartner S, Miller H (eds) *Science and Democracy: Making Knowledge and Making Power in the Biosciences and Beyond*. Routledge, pp 33–55
- IICRC, Institute of Inspection Cleaning and Restoration Certification. (2024). ANSI/IICRC S500 Standard and reference guide for professional water damage restoration. <https://iicrc.org/s500/>
- Institute of Medicine. (2004). *Damp indoor spaces and health* [Report]. The National Academies Press. <https://doi.org/10.17226/11011>
- IPCC, Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability* (Working Group II Contribution to the Sixth Assessment Report). Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg2/>
- Johanning E, Auger P, Morey PR et al (2014) Review of health hazards and prevention measures for response and recovery workers and volunteers after natural disasters, flooding, and water damage: mold and dampness. *Environ Health Prev Med* 19:93–99. <https://doi.org/10.1007/s12199-013-0368-0>
- Kahan DM, Jenkins-Smith H, Braman D (2010) Cultural cognition of scientific consensus. *J Risk Res* 14(2):147–174. <https://doi.org/10.1080/13669877.2010.511246>
- Kazemian N, Lopes L, Hakim L, Ghazanfari A, Bidar A (2019) Environmental factors influencing fungal growth on gypsum board: a critical review. *PLoS ONE* 14(8):e0220556. <https://doi.org/10.1371/journal.pone.0220556>
- Khan AA, Mohan Karuppaiyl FS (2012) Fungal pollution of indoor environments and its management. *Saudi J Biol Sci* 19(4):405–426. <https://doi.org/10.1016/j.sjbs.2012.06.002>
- Lindemann V, Schleiner T, Maier U, Fels H, Cramer B, Humpf HU (2022) Analysis of mold and mycotoxins in naturally infested indoor building materials. *Mycotoxin Res* 38(3):205–220. <https://doi.org/10.1007/s12550-022-00461-3>
- NIEHS, National Institute of Environmental Health Sciences. (2013). *Mold remediation guidance: Health and safety essentials for workers, volunteers, and homeowners* [Guidance document].
- Nielsen, K. F. (2001). *Mould growth on building materials: Minimal relative humidity for growth on wood and gypsum*. PhD Thesis, Technical University of Denmark.
- HUD Office of Healthy Homes and Lead Hazard Control. (2005). *Controlling and preventing household mold and moisture problems: Lessons learned* [Report to Congress]. U.S. Department of Housing and Urban Development.
- Owen R, Macnaghten P, Stilgoe J (2012) Responsible research and innovation: from science in society to science for society, with society. *Sci Public Policy* 39(6):751–760. <https://doi.org/10.1093/scipol/scs093>
- Robbins CA, Swenson LJ, Nealley ML, Kelman BJ, Gots RE (2000) Health effects of mycotoxins in indoor air: a critical review. *Appl Occup Environ Hyg* 15(10):773–784. <https://doi.org/10.1080/10473220050129419>
- Savadori L, Savio S, Nicotra E, Rumiati R, Finucane ML, Slovic P (2010) Expert and public perception of risk from biotechnology. In: Slovic P (ed) *The feeling of risk: New perspectives on risk perception*. Routledge, pp 16–35
- Scheufele DA, Lewenstein BV (2005) The public and nanotechnology: how citizens make sense of emerging technologies. *J Nanopart Res* 7:659–667. <https://doi.org/10.1007/s11051-005-7526-2>
- Siegrist M (2000) The influence of trust and perceptions of risks and benefits on the acceptance of gene technology. *Risk Anal* 20(2):195–204
- Stilgoe J, Owen R, Macnaghten P (2013) Developing a framework for responsible innovation. *Res Policy* 42:1568–1580. <https://doi.org/10.1016/j.respol.2013.05.008>
- UNHCR, United Nations High Commissioner for Refugees. (2025). *Emergency shelter solutions and standards*. <https://emergency.unhcr.org/emergency-assistance/shelter-camp-and-settlement/shelter-and-housing/emergency-shelter-solutions-and-standards>
- Watanabe M, Konuma R, Kobayashi N, Yamazaki A, Kamata Y, Hasegawa K, Kimura N, Tsurikisawa N, Oshikata C, Sugita-Konishi Y, Takatori K, Yoshino H, Hara-Kudo Y (2021) Indoor fungal contamination in temporary housing after the East Japan Great Earthquake Disaster. *Int J Environ Res Public Health* 18(6):3296. <https://doi.org/10.3390/ijerph18063296>
- Yale University Environmental Health & Safety. (2016). *Flood response plan: Mold prevention strategies*.

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