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Understanding regulatory preferences for GMOs and nanotechnology in USA, Israel, and Germany

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Emerging technologies such as genetically modified organisms (GMOs) and nanotechnology are widely regarded as central to future economic growth, social progress, and environmental sustainability, particularly in industrialized countries. Yet they also raise concerns about potential health, environmental, and safety risks. This study investigates public regulatory preferences for GMOs and nanotechnology in the USA, Israel, and Germany, based on a cross-national online panel survey. We identify notable differences in attitudes: participants strongly favour hard regulation for GMOs, while support for similar regulation of nanotechnology is significantly weaker. These differences reflect both perceived risk levels and broader national contexts. Our findings underscore the need for regulatory approaches that are both technology-specific and context-sensitive, recognizing that public acceptance is shaped by the cultural and institutional environments in which technologies are introduced.

Keywords regulatory preferences, genetically modified organisms, nanotechnology, United States, Israel, Germany

1. Introduction

Emerging technologies such as genetically modified organisms (GMOs) and nanotechnology promise significant societal benefits, ranging from increased agricultural productivity to breakthroughs in medicine, materials science, and environmental protection. Over recent decades, GMOs have become widely used in crops, food, and agricultural practices, while nanotechnologies have rapidly entered diverse sectors such as medicine, textiles, cosmetics, and food products. However, these technologies also present complex governance challenges due to their inherent scientific uncertainties, potential health and environmental risks, and divergent societal expectations (Kurath et al. 2014, Roco and Savage 2018, OECD 2023). As governments face growing pressure to regulate these technologies, understanding how the public perceives them and what regulation they support has become essential for ensuring democratic legitimacy, maintaining public trust, and designing effective, socially responsive innovation policies (Burri 2015).

Potential risks and threats posed by GMOs and nanotechnology are of similar nature and magnitude, which has led to controversial public debates in western industrialized countries regarding the development and use of these technologies, despite their considerable high potential (see, *e.g.* (Royal Society and Royal Academy of Engineering 2004; Falkner and Jaspers 2012; Stephan 2012; Hanssen et al. 2018)). This paper investigates how citizens in three countries, the United States, Germany, and Israel, evaluate the need to regulate GMOs and nanotechnology. While both technologies involve uncertainty and possible risk, prior research has shown that GMOs elicit stronger public concern and support for stricter regulation (Falkner and Jaspers 2012, Yue et al. 2015). However, this pattern is neither universal nor uniform. Across countries, people vary in how much regulation they support and how they perceive the associated threats. What explains these differences? And why is there more support for hard regulation of GMOs than nanotechnology, even though both involve unknown risks (Kurath et al. 2014, Burri 2015)?

We argue that regulatory preferences are co-produced by two contextual forces: (1) national regulatory traditions, historical, institutional, and cultural legacies that shape state approaches to risk, precaution, and scientific governance (Mintz 2017, Purnhagen and Wesseler 2021, Spök et al. 2022), and (2) media discourses, which frame technological controversies and influence how risks and benefits are publicly interpreted (Lee et al. 2005, Happer and Philo 2016). Together, these factors shape public attitudes toward different forms of regulation, whether hard (state-imposed, precautionary, and mandatory) or soft (market-based, flexible, and voluntary) (König et al. 2023).

Germany's regulatory culture, for example, emphasizes precaution and deliberative governance, reinforced by a historically sceptical media discourse (Feindt and Kleinschmit 2011, Mintz 2017). In contrast, U.S. governance emphasizes risk management and

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market compatibility, accompanied by media narratives that often highlight innovation and economic promise (Beckwith et al. 2003; Ely et al. 2023; Happer and Philo 2016). Israel presents a hybrid case, combining regulatory pragmatism, limited public debate, and weaker media framing.

To examine these dynamics, we use survey methods to examine the questions of what preferences citizens across the three industrialized countries have regarding the regulation of GMOs and nanotechnology risks and whether certain factors, national regulatory traditions, public debates, and citizens' characteristics, may play a role in this respect. Our empirical strategy compares regulatory preferences for GMOs and nanotechnology (cross-technological dimension) across Germany, the U.S., and Israel (cross-national dimension). We assess support for hard and soft regulatory instruments, and link these preferences to perceived threats and national context.

Our results suggest that citizens generally consider GMOs to be more dangerous for health and the environment than nanotechnology. We also found that people express a stronger inclination toward regulating GMOs than nanotechnology, indicating a significant difference in regulatory preferences between the two technologies. Thus, there were notable differences among the countries in their perceptions of the threat posed by technology and in preferences for regulation, confirming that public preferences are technology-specific. German respondents consistently favour stricter regulation across both technologies, reflecting strong precautionary traditions and critical media discourses. Americans show more support for flexible, market-based regulation, while Israeli responses are more ambivalent, suggesting weaker framing effects and hybrid regulatory institutions (Falkner and Jaspers 2012, Tran et al. 2019).

The study contributes to the literature in three ways. Conceptually, it integrates potential political-institutional and cultural-communicative explanations by linking regulatory traditions and media discourse (Burri 2015, Happer and Philo 2016). Empirically, it provides rare comparative evidence on public regulation preferences across both technology types and countries. Practically, it underscores the importance of aligning regulatory design with public expectations to foster legitimate and adaptive governance (Tosun and Hartung 2020).

The remainder article is organized as follows. The next section introduces the theoretical framework, drawing on the literature on the potential contextual background factors regulatory traditions and media framing. We then present the empirical methodology, survey design, and the main findings. The discussion interprets the results in light of the theoretical expectations and reviews their policy implications. A concluding section summarizes the core insights and outlines future research directions.

1.1 Analytical frameworks

1.1.1 Conceptualizing regulation: Hard and soft modes.

Public regulatory preferences often vary, including whether regulation is needed in the first place and what kind of regulation is appropriate. To capture this variation, we distinguish between hard and soft regulatory modes (König et al. 2023).

- **Hard regulation** refers to mandatory, legalistic, and state-enforced measures, such as formal bans, binding laws, or licensing requirements.
- **Soft regulation**, by contrast, includes voluntary standards, self-regulation, public information campaigns, and market-driven incentives.

While this distinction is analytical, public support often maps onto these categories, revealing underlying expectations about state authority, risk acceptability, and the legitimacy of technical governance (Spök et al. 2022).

The distinction between hard and soft regulation is particularly pronounced for emerging technologies with high uncertainty and contested social meanings. In such cases, regulatory preferences are not only a function of individual risk perception but also shaped by broader institutional and cultural environments that influence how technologies are understood and governed (Burri 2015).

Comparative analysis links GMOs and nanotechnology in regulation, drawing parallels between the technology fields. Studies highlight that lessons learned from the controversy surrounding GMOs shape how nanotechnology is perceived (Kearnes et al. 2006b, Brunel et al. 2018). Additionally, research shows that both fields experience a similar regulatory pattern of alternating between under- and over-regulation, driven by changing public perceptions of risk and the readiness of regulatory frameworks to address emerging technologies (Ludlow et al. 2009). Despite these connections, direct empirical comparisons of actual regulatory preferences between GMOs and nanotechnology still need to be included. While some research has begun to explore consumer preferences for these technologies, showing that nanotechnology evokes less resistance than GMOs (Yue et al. 2015), a comprehensive study of how regulatory preferences differ across countries still needs to be developed.

A common approach is to study correlations between the support for different regulatory instruments, with a particular focus on differing support for soft regulation (*e.g.* industry standards or labels) and hard regulation (*i.e.* governmental regulations through laws or bans). This approach will also guide the analysis here. Contributions on citizens' regulatory preferences are not only scattered over different policy areas, but also the hypothesized determinants on which they focus differ (König et al. 2023). We focus here on the target of the regulation (*e.g.* (Aghion et al. 2010; Pinotti 2012; Harring 2016; Kitt et al. 2021)), and citizens' attitudes toward the desired goals and possible impacts of the regulatory action (Tosun and Hartung 2020). When investigating regulatory preferences, it is not enough to simply look at the absolute support (or refusal) for different forms of regulation. We thus also focus on the correlation between hard and soft regulation, mirroring previous studies on regulatory preferences.

The hard/soft distinction has previously been applied to single technologies or regulatory contexts (Harring 2016, Tosun and Hartung 2020, König et al. 2023). We contribute by applying it simultaneously along two dimensions. By examining preferences for hard and soft regulation across two technologies (GMOs and nanotechnology) and three regulatory cultures (Germany, Israel, and the United States) within a single instrument, we isolate technology-specific preferences from general preferences for state intervention and assess how the distinction applies across diverse national contexts. This two-by-three design allows comparative insights unavailable to single-technology or single-country studies.

1.1.2 Determinants and contextual drivers of regulatory preferences.

Research on public responses to emerging

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technologies has developed along several lines, each operating at a different level of analysis. At the individual level, an extensive socio-psychological literature has identified the determinants that shape technology acceptance, most consistently risk perception, trust, perceived benefit, knowledge, individual differences, and attitudes (Gupta et al. 2012). At the level of meaning-making, research on categorization has shown that the way a technology is named, classified, and semantically grouped with adjacent technologies materially shapes public perception, as citizens transfer established attitudes and controversies from familiar to unfamiliar domains (Poortvliet et al. 2019). At the macro level, work on sociotechnical imaginaries has demonstrated how nationally specific configurations of state, science, and society co-produce distinctive expectations regarding how technologies should be governed (Burri 2015).

These accounts complement each other. Recent qualitative evidence shows that individual-level factors found in socio-psychological studies are valid but changeable. They are shaped by context, past templates, and shared technology histories (Feindt and Poortvliet 2020). Thus, micro-level psychological processes do not operate in isolation. They are influenced by the discursive and institutional environments where opinions form.

The present study primarily operates at the institutional and discursive levels. We draw on co-production as an interpretive lens to examine how national regulatory traditions and documented patterns of media discourse correspond to cross-national variation in citizen-level regulatory preferences for GMOs and nanotechnology. We do not directly test individual-level determinants or measure categorization processes; rather, we treat these as plausible mediating mechanisms operating at adjacent levels of analysis. Our contribution lies in providing systematic comparative evidence on how macro-level contextual differences manifest as observable variation in public preferences for hard and soft regulatory instruments across three countries with distinct regulatory cultures.

1.1.2.1 Technological differences Genetically modified (GM) foods and nanotechnology, which represent ground-breaking achievements in scientific development, each with unique technological innovations and societal challenges. (Youtie et al. 2011, Łojkowski et al. 2015).

GM foods are characterized by altering an organism's genetic makeup to instill desired traits such as enhanced nutritional value or increased resistance to pests (National Human Genome Research Institute n.d.; European Commission, n.d.a.). This direct intervention into the genetic code raises multifaceted concerns (Worsley and Lea 2008, Schmidt et al. 2009, Whittingham et al. 2020) ranging from the potential health risks associated with consuming such foods—underscored by debates over unforeseen allergic reactions or other health implications (Haukenes 2004, Pham and Mandel 2019) to the environmental impacts, including threats to biodiversity and the possibility of unintentional gene transfer to wild species (Wesseler et al. 2011) and extending to profound ethical dilemmas about the manipulation of natural genetic sequences (Font 2011, Gregorowius 2013).

In stark contrast, nanotechnology delves into the manipulation and control of matter on an atomic or molecular scale, creating materials, devices, and systems with novel properties (Centers for Disease Control and Prevention n.d.; European Commission, n.d.b.; Hornyak and Rao 2016). Its applications are wide-ranging, from medical therapies that could revolutionize drug delivery to energy technologies promising enhanced storage capabilities. However, this technological breadth has its concerns. The health and safety implications of nanomaterials, particularly their long-term effects on the human body and the environment, remain under intense scrutiny (Priestly et al. 2007, Chen et al. 2014). In the environmental sphere, the ecological impacts of widespread nanomaterial usage are yet to be fully understood (Godwin et al. 2009, Stander and Theodore 2011), while ethical debates arise over issues such as privacy in the context of nano-surveillance and the potential for military applications (Gorman et al. 2004, Mills and Fleddermann 2005, Umbrello 2019).

The technical differences between GM foods and nanotechnology, ranging from the targeted genetic modifications of living organisms to the manipulation of inorganic matter at the nanoscale, in organic and inorganic systems, underscore their distinct scientific foundations and the unique societal, health, and environmental debates they provoke. The technical differences between GM foods and nanotechnology underscore their distinct scientific foundations and the unique societal, health, and environmental debates they provoke. Additionally, nanotechnology is perceived as less invasive compared to GMOs, due to lower public awareness and knowledge levels. Fuchs and Gazsó (2015) show that most individuals are unfamiliar with nanotechnology's applications and potential risks. Low visibility, combined with general trust in regulatory institutions, lowers the demand for strict oversight compared to GMOs.

1.1.2.2 National Regulatory Traditions and risk governance A key factor that might shape public regulatory preferences is the historical configuration of national institutions and their embedded approaches to technological risk. We define national regulatory traditions as path-dependent governance regimes that influence how states assess, manage, and communicate risk, particularly under uncertainty. State institutions, scientific actors, and societal groups have developed long-standing relationships that shape these traditions, while country-specific media discourses and cultural narratives might further reinforce them (Mintz 2017, Purnhagen and Wesseler 2021).

Germany exemplifies a precautionary regulatory tradition shaped by past crises, most notably the BSE (Bovine Spongiform Encephalopathy) scandal, commonly known as mad cow disease, and anti-nuclear protests, that fostered public distrust in techno-scientific risk management. This has led to institutional commitments to ex ante risk avoidance, high transparency standards, and deliberative public engagement (Feindt and Kleinschmit 2011). Media coverage of GMOs and other emerging technologies often emphasizes ethical dilemmas, health risks, and environmental concerns, framing them as threats to natural integrity and social order (Green et al. 2005, McCauley 2015, Siddiqui et al. 2022). These cultural and institutional factors jointly reinforce strong public support for hard forms of regulation.

The United States, by contrast, operates under a liberal, market-centered regulatory paradigm characterized by cost–benefit analysis, fragmented agency oversight, and a general preference for *post hoc* rather than precautionary intervention (Beckwith et al. 2003, Justo-Hanani and Dayan 2014). Public engagement tends to occur through lobbying and litigation rather than participatory processes. Media narratives frequently highlight innovation,

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consumer choice, and scientific progress, which align with foundational values of individual freedom and economic opportunity (Catacora-Vargas et al. 2018; Ely et al. 2023; Ortega et al. 2020). In this context, support for soft regulation that enables flexibility, and entrepreneurial innovation is more common.

Israel presents a hybrid model, combining centralized regulatory authority with limited public deliberation. Both European and U.S. frameworks have influenced Israel's governance of GMOs and nanotechnology, which reflects a pragmatic approach driven by state-led innovation and the strategic use of technology to address agricultural, environmental, and geopolitical challenges. (Eitan et al. 2023). While public debate is less prominent, regulatory policies are still responsive to external constraints, especially European Union trade requirements that necessitate compliance with stricter standards for exports of GM crops and nano-products (Spök et al. 2022).

These national configurations reveal how public preferences toward emerging technologies are not formed in a vacuum but co-produced through institutional histories, media framings, and societal expectations. Germany's caution, Israel's pragmatism, and the United States' market orientation are deeply embedded in their respective regulatory traditions, helping to explain observed cross-country differences in support for hard *versus* soft forms of regulation.

1.1.2.3 Media framing as a contextual background influencing the cultural meaning of risk National traditions do not operate in isolation. Media discourses might also act as cultural amplifiers that shape how the public interprets uncertainty and assigns legitimacy to different regulatory options (Happer and Philo 2016). Through framing, media can define what is at stake, who is responsible, and whether a technology is viewed as threatening or promising (Lee et al. 2005).

For instance, GMOs have often been portrayed in European media as tied to food safety, ethical controversy, and corporate overreach, intensifying demand for precautionary regulation (Falkner and Jaspers 2012). Nanotechnology, by contrast, is frequently framed in optimistic terms, emphasizing scientific progress and consumer benefits (Kurath et al. 2014, Tran et al. 2019). These framing asymmetries also vary by country. In Germany, GMO coverage has been alarmist and politicized, reinforcing a public culture of caution. In the U.S., media narratives typically highlight scientific consensus and regulatory confidence, which tempers public pressure for strict controls (Ely et al. 2023). In Israel, the media environment is less saturated with these debates, resulting in weaker framing effects.

Finally, several studies have shown that the media, as the main source for disseminating information and shaping public opinion, wields considerable power in framing and directing the discourse on complex issues such as emerging technologies (Gamson and Modigliani 1989, Lee et al. 2005, Happer and Philo 2016). We adapt this idea, which focuses on the nature of the media landscape, to our specific context of GM food and nanotechnology in Germany, Israel and the USA as a potential contextual background variable.

In Germany, the media landscape is known for its rigorous and meticulous reportage. Historically, German media outlets have adopted a cautious approach when discussing technological innovations in food. GM foods' potential risks, ethical dilemmas, and societal implications are frequently spotlighted, orienting the narrative toward a risk-centric view.

Additionally, civic organizations often receive coverage in the media, which helps bring attention to their advocacy efforts. For example, organizations like Greenpeace frequently appear in media reports, where their campaigns addressing GM foods are highlighted, contributing to the broader public discourse and may reinforce the prevailing scepticism surrounding GM foods in Germany and across the European Union (McCauley 2015, Bennett and Radford 2017).

The media landscape in the USA is vast, diverse, and multifaceted. This diversity results in various voices, each presenting its perspective on GM foods and nanotechnology. While some outlets might emphasize these technologies' commercial potential and benefits, others might spotlight potential risks and ethical concerns, leading to a polarized and often contentious debate (Lindberg et al. 2023b). The role of interest groups, activists, and lobbyists in shaping media narratives cannot be understated. These entities, with their vested interests, often utilize media platforms to sway public opinion, making the discourse dynamic and ever evolving (Beckwith et al. 2003, Tran et al. 2019, Furgurson et al. 2023). The American media also plays a pivotal role in hosting public debates, town halls, and open forums, ensuring that a broad spectrum of voices is heard, reflecting the democratic ethos of the nation.

In Israel, the media landscape regarding GMOs and nanotechnology is limited and biased. Traditionally, the Israeli media has taken a supportive stance toward technological innovation, including GMOs and nanotechnology, reflecting the social and economic narrative of a start-up nation (Senor and Singer 2010). Potential risks, legal and ethical issues are mostly neglected in media coverage. Moreover, despite the potential risks of GMOs and nanotechnology, social scientists and research policy experts have paid very little attention to risk regulation and policy in Israel (exceptions include (Justo-Hanani and Dayan 2015)). Although there is a vast literature and extensive academic activity worldwide, few works address these aspects from the Israeli perspective, focusing mainly on business and commercial applications and some aspects of public perception related to 'red' biotechnology (Prainsack and Firestine 2006, Rosenbaum et al. 2007). Genetic engineering and nanotechnology safety are rarely discussed in the local media. The Israeli media play a minor role in hosting public debates on the risks and uncertainties of these technologies.

In conclusion, with its profound influence and reach, media framing can be addressed as an important contextual background factor influencing the cultural meaning of risk in a country, shaping, directing, and amplifying the discourse on GM foods and nanotechnology across different national contexts. The narratives it crafts, the perspectives it emphasizes, and the voices it amplifies all converge to mould public perception and understanding of these complex technological advancements.

The media's role in Germany and the USA illustrates its power in framing public debates on technology, often amplifying risks and ethical dilemmas associated with technological innovations. The polarized and dynamic nature of media-driven discourse, which is influenced by interest groups and civil society organizations, highlights the media's ability to shape public opinion and regulatory preferences.

1.1.2.4 Co-production of regulatory preferences We draw on co-production as an interpretive lens to make sense of cross-national variation in regulatory preferences. Citizens do not

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assess technologies in a vacuum. Instead, their attitudes reflect embedded assumptions about how risk should be governed, assumptions shaped by national experiences and mediated through public discourse (Burri 2015). The framework links Macro-level governance regimes (precautionary versus liberal), Meso-level media environments (alarmist versus optimistic framing), and Micro-level citizen attitudes toward regulation. Rather than testing the framework's causal mechanisms, we use it to organize our interpretation of how institutional traditions and discursive environments correspond to observed patterns of public preference, for instance, why Germans support stricter regulation across both technologies, while Americans show more variation depending on perceived risk or benefit. It also might help to clarify why GMOs elicit more substantial support for hard regulation than nanotechnology, even when both are scientifically uncertain, because they are framed and institutionalized differently. By integrating institutional and cultural approaches, we move beyond purely individual-level or rational-choice accounts and provide a more holistic theory of how the public evaluates technological governance.

1.1.2.5 Expected patterns of regulation support across technologies and countries Building on this foundation, we now develop specific expectations about how technology type, threat perception, and national context shape public preferences for hard *versus* soft regulation. Public preferences for regulating emerging technologies reflect the technology's characteristics and the institutional and discursive context in which citizens operate.

First, we hypothesize that citizens are more likely to support hard forms of regulation, mandatory, state-enforced, and precautionary measures, for genetically modified organisms (GMOs) than for nanotechnology. This difference stems from the historically more contentious framing of GMOs, especially in European contexts, where media and public debates have linked them to food safety concerns, ethical controversies, and environmental risks. In contrast, nanotechnology has often been portrayed as innovative, beneficial, and less politically contested.

Second, perceived risks are central in shaping support for hard regulation. Specifically, individuals who perceive greater health or environmental risks from a technology tend to favour precautionary regulation. Such threat perceptions likely increase demand for state intervention and reduce support for flexible, market-based, or voluntary governance.

Third, we expect systematic cross-country differences driven by national regulatory traditions and media environments. Given the country's strong precautionary tradition and politicized risk discourse, we expect German citizens to strongly support hard regulation. In Israel, where regulatory institutions are more centralized and media discourse less polarized, we expect moderate support for hard regulation. In the United States, where regulation emphasizes market-oriented principles and scientific risk assessment, we anticipate the lowest support for hard regulation.

Finally, we anticipate an interaction between technology type and national context. We expect the contrast in public preferences between GMOs and nanotechnology to be most pronounced in Germany, where discursive and institutional distinctions between the two are particularly stark. In the United States, where both technologies are typically framed as manageable and innovation-friendly, we expect regulatory preferences to differ less sharply between them.

2. Method

2.1 Sample and procedure

The survey was conducted in November 2019 using two professional online panel services: Panel4All (http://www.panel4all.co.il/) and Dynata (https://www.dynata.com/). Panel4All recruited a sample of adult respondents from Israel, while Dynata recruited samples of adult respondents from the USA and Germany. The final sample included 2,482 respondents: 807 Israelis, 846 Germans, and 829 Americans. Among respondents with valid age data, ages ranged from 18 to 80. The sample was 47% male overall, with male respondents comprising 49% of the Israeli sample, 49% of the German sample, and 42% of the U.S. sample. Ethical approval for the study was granted by the Tel Aviv University Institutional Review Board, and all participants provided informed consent after being assured of anonymity.

Although the survey was conducted in 2019, the regulatory frameworks and public discourse surrounding GMOs and nanotechnology have remained broadly consistent in Germany, Israel, and the USA. These technologies continue to raise ethical, health, and environmental concerns and feature in ongoing policy debates; even so, we have seen since 2019 new technological developments (e.g. gene editing; new nano-enabled products), which have also caused new regulatory frameworks (e.g. an updated New Genomic Techniques (NGT) legislation of the EU from 2025). The findings thus provide a relevant baseline for understanding public attitudes that remain pertinent to current and future regulatory discussions.

2.2 Measures

***Sampling Structure*:** Half of the sample was randomly assigned by the survey software to answer questions about GMOs first, followed by questions on nanotechnology. The other half responded to nanotechnology-related questions first.

***Regulatory Preferences*:** Respondents rated their agreement with the following regulatory preference statements on a scale from 1 (completely disagree) to 5 (definitely agree):

1. The government should implement tight regulations (comprehensive safety assessment) before GMOs/nanotechnology products enter the market ('tight regulations').
2. Products containing GMOs/nanotechnology should be clearly labelled ('labels').
3. The industry should define its own 'standards of behaviour' regarding GMOs/nanotechnology ('industry standards').
4. No regulation is needed for GMO/nanotechnology ('no regulation').
5. The government should ban all products containing GMOs/-nanotechnology ('bans').

Note: For descriptive comparison between GMOs and nanotechnology, we used the reversed 'no regulation' item as a single-item indicator of general support for regulation. This indicator captures rejection of the view that no regulation is needed and should not

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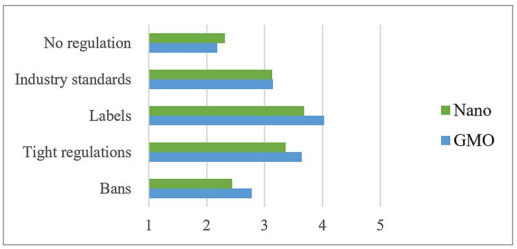


Figure 1 Comparison of regulatory preferences for GMOs and nanotechnology.

be interpreted as a validated multi-item index. The 'bans' item was analysed as a distinct restrictive-regulation item. However, we interpret it cautiously because support for banning all products may also reflect broader opposition to the technology, moral rejection, or heightened risk concern, rather than a regulatory preference alone.***Threat Level*:** Respondents rated their agreement with statements regarding perceived threats on a scale of 1 (completely disagree) to 5 (definitely agree): 'GMOs/nanotechnology endanger human health' and 'GMOs/nanotechnology endanger the environment.'

***Socio-demographic Background*:** Participants provided socio-demographic information, including age, gender, and country of residence.

2.3 Data analysis

Data analysis was conducted to test the study's hypotheses. A paired-samples *t*-test compared the single-item indicator of general support for regulation and support for restrictive regulation between GMOs and nanotechnology (H1). Pearson correlation analysis assessed the relationship between perceived threat levels and regulation preferences (H2). An ANOVA tested differences between countries in threat perception and regulatory preferences (H3).

3. Results

The analysis begins with an overview of regulatory preferences. Overall, respondents show a stronger preference for regulating GMOs compared to nanotechnology (Fig. 1). To test this difference, paired-samples t-tests compared the reverse-coded 'no regulation' item, used as a single-item indicator of general support for regulation, and support for restrictive regulation across the two technologies.

A paired-samples *t*-test comparing the reverse-coded 'no regulation' item showed significantly higher general support for regulating GMOs (M = 3.82, SD = 1.24) than nanotechnology (M = 3.69, SD = 1.21), t(2481) = 5.35, $P < .001$.

When examining preferences for strict regulatory measures, there was a significant difference in the scores for banning GMOs (M = 2.78, SD = 1.31) *versus* banning nanotechnology (M = 2.44, SD = 1.20), t(2481) = 14.30, $P < .001$. Additionally, scores for hard regulation showed a significant difference, with higher support for GMOs (M = 3.64, SD = 1.23) than for nanotechnology (M = 3.36, SD = 1.23), t(2481) = 12.03, $P < .001$.

These results support Hypothesis H1, indicating that respondents display a stronger inclination toward regulating GMOs than nanotechnology.

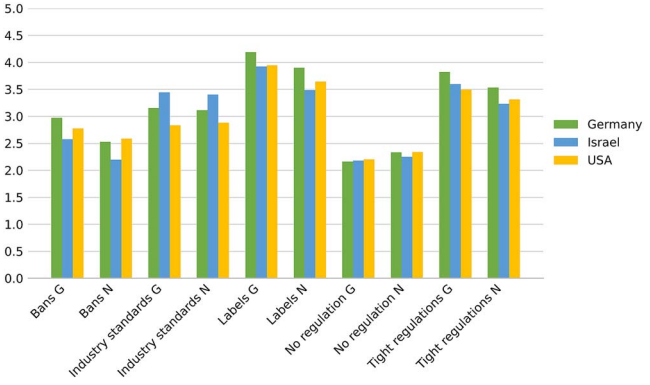


Figure 2 Regulation preferences by country, 'N' represents nanotechnology and 'G' represents GMOs.

To assess the second hypothesis, Pearson correlation analyses were conducted to examine the relationship between perceived threat levels and preferences for strict regulation. The results are presented in Tables 1 and 2, confirming a clear positive association: the more strongly a technology is perceived as a threat, particularly to human health, the greater the support for state-enforced, precautionary regulation. This pattern holds across both GMOs and nanotechnology, suggesting that perceived threat is a consistent driver of demand for more interventionist regulatory approaches.

For GMOs perceived as a health threat, there is a strong positive correlation with preferences for both bans (Pearson = 0.698, $P < .001$) and hard regulation (Pearson = 0.528, $P < .001$). Similarly, when GMOs are seen as an environmental threat, there is a significant correlation with preferences for bans (Pearson = 0.639, $P < .001$) and tight regulation (Pearson = 0.495, $P < .001$).

The results for nanotechnology were similar, though slightly weaker. Perceiving nanotechnology as a health threat is positively correlated with preferences for bans (Pearson = 0.663, $P < .001$) and hard regulation (Pearson = 0.447, $P < .001$). Likewise, viewing nanotechnology as an environmental threat correlates with preferences for bans (Pearson = 0.614, $P < .001$) and hard regulation (Pearson = 0.465, $P < .001$).

An ANOVA analysis was conducted to examine differences between countries in perceived threat levels and regulatory preferences for GMOs and nanotechnology. Figure 2 provides an overview of these preferences across the countries studied. Notably, Israeli respondents have the highest mean preference for industry standards for both technologies, while German respondents show the highest mean preference for hard regulation. Conversely, Israelis report the lowest mean scores regarding bans on these technologies.

For GMOs, German respondents exhibit the highest mean for banning, whereas the difference between American and German respondents on banning nanotechnology is less pronounced.

To assess cross-national differences in regulatory preferences, we conducted a one-way ANOVA. The ratings for various statements differed significantly across the three countries (see Table 3, $P < .005$), except for the 'no regulation' statement for both technologies, where no significant difference was found. Due to a violation of the homogeneity of variances assumption (see Table S1), we also performed Welch's test (Glantz and Slinker 2001). The Welch's test results confirmed significant differences

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Table 1 Pearson correlations associating attribution of GMOs to health and environmental threats to preferences for hard regulation of the technology (N = 2,482).

	1	2	3	4
GMOs are dangerous for humans' health	1			
GMOs are dangerous for the environment	0.773**	1		
Bans (GMOs)	0.698**	0.639**	1	
Hard regulations (GMOs)	0.528**	0.512**	0.495**	1

**Correlation is significant at the 0.01 level (2-tailed).

Table 2 Pearson correlations associating attribution of N&N to health and environmental threats to preferences for hard regulation of the technology (N = 2,482).

	1	2	3	4
Nanotechnology is dangerous for humans' health	1			
Nanotechnology is dangerous for the environment	0.823**	1		
Bans (nanotechnology)	0.663**	0.614**	1	
Hard regulations (nanotechnology)	0.447**	0.465**	0.420**	1

**Correlation is significant at the 0.01 level (2-tailed).

among the countries, again excluding the 'no regulation' statement (see Table S2, $P < .005$).

For post hoc analysis, Tamhane's T test was applied to account for multiple comparisons (see Table S3). Significant mean differences greater than 0.5 (absolute value) are marked in bold. Overall, the results indicate that German respondents, consistent with the country's strong regulatory tradition and active public debate around technology, show a greater preference for hard regulation. In contrast, Israeli respondents tend to express greater acceptance of soft regulatory approaches. These patterns underscore the influence of national regulatory cultures on public preferences.

4. Discussion

Our findings provide nuanced insights into public attitudes toward the regulation of emerging technologies, specifically GMOs and nanotechnology, across three countries with distinct regulatory traditions: Germany, Israel, and the USA. These differences reflect broader socio-cultural, historical, and regulatory contexts, illustrating that national differences can shape citizens' regulatory preferences. Our study corroborates and expands on previous literature, which has identified technology-specific attitudes and national influences as significant determinants of regulatory preferences (*e.g.* (Ludlow et al. 2009; Justo-Hanani and Dayan 2015)).

4.1 Regulatory preferences for GMOs and nanotechnology

Our results indicate that, overall, respondents show stronger regulatory preferences for GMOs compared to nanotechnology, with significantly greater support for tighter regulations and bans on GMOs (see Fig. 1 and Table 3). The paired-samples *t*-test revealed a significant difference in preferences for hard regulation between GMOs and nanotechnology ($t(2481) = 12.03$, $P < .001$), suggesting that citizens view GMOs as requiring more stringent regulation. This aligns with earlier studies which have shown that the public perceives GMOs as riskier due to factors such as genetic manipulation, which is often viewed as a disruption of natural processes (Falkner and Jaspers 2012, Whittingham et al. 2020).

The stronger support for regulating GMOs may reflect heightened public sensitivity to genetic interventions in food production, a domain that directly affects human health and environmental sustainability. These findings are consistent with Kearnes et al. (2006b) and Schmidt et al. (Schmidt et al. 2009), who argue that public apprehension surrounding GMOs has influenced the public perception of other emerging technologies, such as nanotechnology. However, nanotechnology, which is often framed within the context of advanced materials and consumer products, may appear less intrusive to respondents, resulting in comparatively lower support for strict regulation. This difference in perception underscores the importance of considering the specific nature of a technology when analysing regulatory preferences.

4.2 Perceived threats and regulatory preferences

The study found significant correlations between perceived health and environmental threats posed by GMOs and nanotechnology and preferences for hard regulation (Tables 1 and 2). Respondents who viewed GMOs as a greater threat to human health were substantially more likely to endorse bans and mandatory regulatory measures (Pearson = 0.698 and 0.528, respectively, $P < .001$). A similar but slightly weaker trend was observed for nanotechnology (Pearson = 0.663 for bans and 0.447 for hard regulation, $P < .001$). This reinforces the conceptual framework suggesting that public concerns about health and environmental impacts are key drivers of regulatory preferences (Kearnes et al. 2006a).

The correlation between threat perception and regulatory preference aligns with the risk-centered regulatory framework, wherein the perceived severity and immediacy of risks influence public demand for regulatory intervention (Ludlow et al. 2009,

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Table 3 ANOVA results for perceived threats and regulatory preferences for GMOs and nanotechnology by country.

		Sum of Squares	Df	Mean Square	F	Sig.
GMO is dangerous for humans' health	Between Groups	47.377	2	23.689	16.674	0.000
	Within Groups	3521.945	2,479	1.421		
	Total	3569.322	2,481			
GMO is dangerous for the environment	Between Groups	114.037	2	57.018	39.152	0.000
	Within Groups	3610.218	2,479	1.456		
	Total	3724.255	2,481			
Nanotechnology is dangerous for humans' health	Between Groups	121.712	2	60.856	47.407	0.000
	Within Groups	3182.290	2,479	1.284		
	Total	3304.002	2,481			
Nanotechnology is dangerous for the environment	Between Groups	153.313	2	76.657	56.064	0.000
	Within Groups	3389.546	2,479	1.367		
	Total	3542.859	2,481			
Bans G	Between Groups	63.814	2	31.907	18.954	0.000
	Within Groups	4173.082	2,479	1.683		
	Total	4236.896	2,481			
Tight regulations G	Between Groups	45.665	2	22.833	15.204	0.000
	Within Groups	3722.880	2,479	1.502		
	Total	3768.545	2,481			
Labels G	Between Groups	36.811	2	18.406	14.349	0.000
	Within Groups	3179.925	2,479	1.283		
	Total	3216.737	2,481			
Industry standards G	Between Groups	153.599	2	76.800	45.419	0.000
	Within Groups	4191.763	2,479	1.691		
	Total	4345.362	2,481			
No regulation G	Between Groups	0.671	2	0.335	0.217	0.805
	Within Groups	3831.104	2,479	1.545		
	Total	3831.775	2,481			
Bans N	Between Groups	71.924	2	35.962	25.533	0.000
	Within Groups	3491.510	2,479	1.408		
	Total	3563.435	2,481			
Tight regulations N	Between Groups	40.334	2	20.167	13.463	0.000
	Within Groups	3713.373	2,479	1.498		
	Total	3753.707	2,481			
Labels N	Between Groups	71.025	2	35.512	24.497	0.000
	Within Groups	3593.691	2,479	1.450		
	Total	3664.716	2,481			
Industry standards N	Between Groups	111.861	2	55.931	36.017	0.000
	Within Groups	3849.623	2,479	1.553		
	Total	3961.485	2,481			
No regulation N	Between Groups	3.842	2	1.921	1.317	0.268
	Within Groups	3615.370	2,479	1.458		
	Total	3619.212	2,481			

Tosun and Hartung 2020). For example, concerns about health risks linked to GMOs, such as potential allergic reactions or unintended gene transfer, may explain the stronger preference for hard regulation of GMOs compared to nanotechnology, whose applications in areas like electronics and textiles are seen as more distant from direct human health implications (Priestly et al. 2007, Pham and Mandel 2019).

4.3 National Differences in regulatory preferences

Consistent with the expectation that national regulatory traditions can shape public preferences, our ANOVA and Welch's test results reveal significant cross-country differences in support for regulatory measures, with the exception of the 'no regulation' statement

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(see Table 3 and Fig. 2). German respondents demonstrated the highest support for hard regulation, consistent with the country's regulatory tradition and cautionary approach to emerging technologies, a trend previously highlighted in studies by Feindt and Kleinschmit (2011) and Purnhagen and Wesseler (2021).

Germany's regulatory stance can be attributed to its historical experiences, such as the BSE crisis, which fostered a culture of scepticism toward food technologies (Green et al. 2005, Lindberg et al. 2023a). This contrasts with Israel, where respondents displayed comparatively lower support for stringent regulation, likely due to a more pragmatic orientation toward technological innovation in response to the country's unique environmental and geopolitical challenges (Eitan et al. 2023). Israel's approach to emerging technologies reflects a practical orientation, where innovation is often viewed as essential to addressing the nation's agricultural and environmental constraints. These results are consistent with the findings of Justo-Hanani (2024), who notes that Israeli regulatory frameworks for GMOs and nanotechnology tend to align with commercial priorities and trade relations rather than precautionary principles.

In the USA, a generally positive stance toward technological progress, coupled with the influence of large biotech corporations, contributes to a more commercially driven regulatory approach (Bain and Dandachi 2014, Baum et al. 2023). This market-oriented regulatory framework likely influences public attitudes, as Americans generally express lower levels of concern over GMOs and nanotechnology compared to German respondents. The differences observed across these three countries highlight the role of historical, cultural, and economic factors in shaping public opinion and regulatory preferences for emerging technologies.

4.4 Media influence on public opinion and regulatory preferences

Although the survey did not directly assess individual media exposure, the observed cross-national differences in regulatory preferences can also be interpreted in light of documented media discourse patterns. Our findings are consistent with the expectation that media framing as a contextual cultural background variable, can shape how citizens interpret the risks and legitimacy of emerging technologies. In German and American media landscapes in particular presenting polarized narratives about the risks and benefits of emerging technologies (Happer and Philo 2016, Lindberg et al. 2023b). German media, known for its critical stance on GMOs, frequently emphasizes potential risks and ethical issues, likely contributing to higher support for tight regulation among German respondents (McCauley 2015). Similarly, the diverse media landscape in the USA allows for a dynamic discourse shaped by interest groups and civil society organizations, leading to a broad spectrum of opinions on technology regulation (Tran et al. 2019).

A closer look at the differences in technological familiarity, framing, and perceived proximity to daily life provides further insight into why respondents may perceive nanotechnology as less risky than GMOs. Nanotechnology is often associated with advancements in electronics, materials, and medical devices, which may feel less invasive or ethically concerning to people compared to altering the genetic structure of food. Nanotechnology's applications are also often framed as improvements in efficiency or convenience, which might make them seem less threatening.

GMOs, by contrast, are directly associated with food, which people consume daily, making any perceived risks seem closer and more personal. In contrast, many applications of nanotechnology feel more abstract or distant, such as in industrial or high-tech contexts, potentially reducing perceived personal risk.

Media framing might also play a role here; the media often emphasizes the ethical and environmental controversies surrounding GMOs, whereas coverage of nanotechnology tends to highlight its innovative aspects and medical breakthroughs. This difference in media framing could shape public perception, making GMOs seem riskier.

Lastly, public understanding of nanotechnology is generally lower than that of GMOs. This lack of familiarity can result in less critical assessment or an 'unknown but trusted' mindset, especially if the media and government authorities are not emphasizing the risks.

In contrast, the Israeli media presents a largely supportive view of technological innovation, often downplaying potential risks in favour of emphasizing the benefits of innovation (Senor and Singer 2010). This may explain the comparatively lower support for stringent regulation observed among Israeli respondents. The influence of media in shaping regulatory preferences is consistent with Gamson & Modigliani's theory (1989), which posits that media framing plays a central role in shaping public discourse on complex issues. The findings suggest that the degree of media-driven debate may significantly impact public support for regulation, as reflected in the divergent preferences across the three countries.

4.5 Limitations, and future research

This study has several limitations that should be acknowledged and addressed in future research.

First, while the survey captures regulatory preferences and perceived risks, it does not explore the underlying motivations behind these attitudes. The data do not allow us to assess how individuals interpret or justify their views. National differences in regulatory tradition and media framing might serve as plausible contextual background factors that help explain national differences. However, we do not know in detail how they influence individual views and attitudes. Future research should incorporate qualitative methods such as semi-structured interviews, focus groups, or open-ended survey items to explore the reasoning processes and contextual factors that shape public opinion on emerging technologies.

Second, sampling transparency is limited. The study relies on online panel samples recruited by professional survey providers. Although the samples were structured to approximate the adult populations in Israel, Germany, and the USA, the panel providers did not disclose full recruitment procedures, invitation flows, eligibility screening, or response rates. This limits the strength of claims about national representativeness. In addition, the U.S. sample includes a gender imbalance, with 59% female respondents, which may influence perception patterns. The cross-country comparisons should therefore be interpreted as evidence of patterned variation in regulatory preferences among online panel respondents, rather than as precise estimates of national population attitudes.

Third, the use of online panels and self-reported survey responses introduces potential biases. Respondents may lack

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substantive knowledge about GMOs and nanotechnology or may provide socially desirable answers. To address this, future research should incorporate objective knowledge measures, comprehension checks, or experimental designs that control for information exposure. Triangulating self-reported attitudes with behavioural or observational data could also improve validity. At the measurement level, the 'ban all products' item may conflate generalized technology opposition with preferences for a specific regulatory instrument. In addition, the overall regulatory support indicator relies on a single reversed item rather than a validated multi-item scale. Future studies should develop purpose-built multi-item scales to better distinguish technology rejection, general support for regulation, and preferences for specific regulatory instruments.

Fourth, the study treats national populations as homogeneous, masking potential variation by key factors such as education, political ideology, religiosity, and geography. This limits insight into the internal diversity of public opinion. Future research should perform subgroup analyses to examine within-country variation and test how sociodemographic and attitudinal factors interact with regulatory preferences.

Fifth, the study includes only three industrialized countries—Germany, Israel, and the United States. This limits generalizability to other contexts, especially low- and middle-income countries or those with different regulatory and cultural environments. Subsequent studies should expand the sample to include countries from a broader range of regions, development levels, and governance systems. This would allow for richer cross-national comparisons and enhance the global relevance of the findings.

Sixth, the study provides a cross-sectional snapshot from 2019. Public attitudes toward emerging technologies are dynamic and may shift due to new developments, media coverage, or political events. This is especially important in fast-developing fields like GMOs and nanotechnology, where we have seen tremendous achievements in recent years (*e.g.* gene editing; new nano-enabled products), which have also led to new regulatory frameworks. Longitudinal or panel studies are needed to track how public opinion evolves over time. Time-series surveys or repeated cross-sectional studies can capture the effects of specific triggers (*e.g.* regulatory changes or technological controversies) on public perceptions.

Together, these improvements would enhance the depth, validity, and applicability of research on public attitudes toward emerging technologies. A multi-method, cross-national, and longitudinal research agenda is essential for informing responsive and context-sensitive regulatory policy. Operationalizing context-sensitive regulation requires replacing static, 'one-size-fits-all' frameworks with dynamic approaches. Effectively governing emerging technologies across diverse national contexts demands an agile framework that balances innovation, institutional constraints, and societal inclusivity to foster trust and legitimacy.

4.6 Categorization and the boundaries of 'GMOs' as an object of study

Our 2019 instrument treated GMOs as a single category. Recent communication research, however, indicates that legal categorizations can spill over to mental categorizations: when an unfamiliar technology is placed in the same basket as a familiar and contested one, established attitudes are transferred from the latter to the former, even when the underlying risks differ (Poortvliet et al. 2019). This matters for our findings. Under EU law, since the 2018 Court of Justice ruling, organisms obtained from most New Plant Breeding Technologies, including gene editing, are legally defined as GMOs, although the European Commission's 2023 proposal signalled possible differentiation. Following the categorization argument, citizen preferences expressed toward GMOs should be read as preferences toward the category as it is currently constituted, not toward any specific modification technique. Our results, therefore, characterize public preferences toward GMOs as the term was understood in 2019 public discourse, a category dominated by transgenic applications. As gene editing gains public visibility and the regulatory landscape shifts, future research should disaggregate modification techniques to test whether the patterns documented here hold at finer levels of categorical resolution.

5. Conclusion

This study reveals apparent cross-country differences in public attitudes toward regulating GMOs and nanotechnology. These differences can be interpreted as the result of a combination of perceived risks, national regulatory traditions, and patterns of media discourse. German respondents favoured more stringent regulation, consistent with the country's precautionary legacy and its history of critical public debate. In contrast, respondents in Israel and the United States supported more flexible regulatory approaches, aligning with their more pragmatic or market-oriented regulatory cultures.

These patterns underscore the need for context-sensitive and communicatively legitimate governance. Public attitudes are not uniform; national experiences, institutional legacies, cultural values, and public communication shape them. Policymakers should consider these contextual factors, not to adopt public opinion uncritically, but to ensure that regulatory frameworks remain socially attuned, epistemically credible, and democratically legitimate. Moreover, treating GMOs and nanotechnology as monolithic technologies does not fit their distinct scientific realities (especially with respect to the variety of technologies within these categories, e.g. NGT, Transgenesis, top-down and bottom-up nano), and regulatory frameworks tailored specifically to each are required.

Our findings suggest that effective governance requires adaptive, differentiated regulatory strategies that respond to a technology's specific characteristics and the social context into which it is introduced. While harmonization may be desirable in some areas, rigid, one-size-fits-all models risk provoking public resistance and eroding legitimacy.

For scholars, this study highlights the value of integrating cross-country comparisons with close attention to media framing and institutional context. Future research should examine how public attitudes evolve in response to new technological applications, political shifts, and changes in discursive framing. In addition, alternative explanations, such as trust in institutions and regulatory frameworks, political ideology, and power relations among different economic, social, and environmental interest groups in a country, should be considered. Although our findings draw on data from 2019, they remain relevant due to the continued persistence of national regulatory cultures and the relative stability

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of media narratives surrounding these technologies. Longitudinal and cross-regional studies, including countries beyond the industrialized West, are essential for developing a more global and dynamic understanding of regulatory preferences.

Ultimately, advancing socially responsive and context-sensitive governance of GMOs and nanotechnology will depend on technological innovation and a deeper understanding of how publics engage with risk, responsibility, and the institutional legitimacy of regulation.

Author contributions

Felix Kurz (Conceptualization, Funding acquisition, Investigation, Software, Validation, Writing—original draft, Writing—review & editing), Ronit Justo-Hanani (Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing—review & editing), Shira Bukchin-Peles (Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft), Stefan Wurster (Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing—original draft)

Supplementary material

Supplementary material is available at *Science and Public Policy Journal* online.

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Data availability

The data that support the findings of this study are available from the corresponding author (Felix Kurz) upon reasonable request. The raw data are not publicly available due to privacy restrictions. Derived data and analytic code are stored in a public repository and will be shared via DOI once the manuscript is accepted.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT und Claude in order to For spelling, grammar, and structure. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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