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Article

The Risks of Biotechnology from the Perspective of Scientists: A Systematic Review of Publications from the Last 20 Years

César Cisternas Irarrázabal[1], Arturo Vallejos-Romero[2], Minerva Cordovés-Sánchez[3], Felipe Sáez-Ardura[4]

[1] Master's Degree in Social Sciences. Universidad de la Frontera. ORCID: 0000-0002-4510-4239. Email: cesar.cisternas@ufrontera.cl
[2] Doctor of Social Sciences Research. Professor in the Department of Social Sciences at the University of La Frontera. ORCID: 0000-0002-0393-7275. Email: arturo.vallejos@ufrontera.cl
[3] Doctor of Agri-Food Sciences and Environment. University of La Frontera. ORCID: 0000-0002-0513-7837. Email: minerva.cordoves@ufrontera.cl
[4] Doctor of Social Sciences. University of La Frontera. ORCID: 0000-0001-9472-5552. Email: felipe.saez@ufrontera.cl

RESUMEN
Desde su emergencia, las biotecnologías han generado múltiples controversias respecto de sus riesgos. En las últimas décadas, este campo ha tenido un desarrollo exponencial, emergiendo nuevas técnicas de ingeniería genética como el CRISPR-Cas9, sistemas libres de células y otras herramientas de biología sintética. Con esto en mente, este trabajo realiza una revisión sistemática de la investigación sobre la percepción de los investigadores del ámbito de la biotecnología acerca los riesgos de estas tecnologías. La revisión analizó un corpus de 25 publicaciones indexadas en Web of Science, Scopus y Dimensions en los últimos 20 años. Los resultados indican que, desde la perspectiva de los científicos, la biotecnología presenta pocos o ningún riesgo. Asimismo, los investigadores del área procesan el no-conocimiento y la incertidumbre de un modo radicalmente diferente al público general, considerando a estos últimos, muchas veces, como carentes del conocimiento científico necesario para participar válidamente en el debate sobre los riesgos de la biotecnología.
Palavras-chave: biotecnología; riesgos; científicos; revisión sistemática.

ABSTRACT
Since their emergence, biotechnologies have generated multiple controversies regarding their risks. In recent decades, the field has developed exponentially, with the emergence of new genetic engineering techniques such as CRISPR-Cas9, cell-free systems, and other synthetic biology tools. With this in mind, this paper conducts a systematic review of research on biotechnology researchers' perceptions of the risks of these technologies. The review analyzed a corpus of 25 publications indexed in Web of Science, Scopus, and Dimensions over the last 20 years. The results indicate that, from the perspective of scientists in the field, biotechnology presents little or no risk. In addition, researchers in the field deal with non-knowledge and uncertainty in ways that differ radically from the general public, often considering the latter to lack sufficient scientific knowledge to participate validly in debates about the risks of biotechnology.
Keywords: biotechnology; risks; scientists; systematic review.

Introduction

The transition to modernity involved a radical transformation in the way society understood unwanted outcomes and uncertainty. In effect, these ceased to be seen as products of hidden natural forces or inaccessible divine intentions, giving rise to the idea of risk, whereby such undesirable outcomes or possible unknown consequences began to be directly associated with human decisions (Giddens 1990; Luhmann 2006). Given the ubiquity of risk in society since the second half of the 20th century, intrinsically linked to the model of production and development, it has been proposed to understand it as a risk society (Beck 1998, 2002).

Scientific activity, a fundamental pillar of the economic-productive framework of late capitalism, has reached such complex levels of development that it must constantly deal with uncertainty and, by extension,

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risk. Thus, at present, advances in scientific knowledge and the refinement of cutting-edge technologies mean that risk is not merely an external perception of the potential effects of new discoveries and inventions. On the contrary, the high levels of uncertainty implicit in theoretical and applied developments make risk a necessary condition for the deployment of research possibilities (Luhmann 2006).

Over the last few decades, there have been considerable advances in various fields of biology, such as molecular, cellular, and systems biology. During this period, for example, new genetic engineering techniques have been developed and the emergence of synthetic biology has been consolidated, a subdiscipline that aims to construct or redesign biological parts, structures, devices, and systems that may be useful for theoretical biology or the production of chemicals, industrial enzymes, biofuels, or medicines (Lu 2020; Rylott & Bruce 2020; Voigt 2012).

On numerous occasions and in many contexts, technological developments in the field of biological sciences have generated controversy and public debate. Such public controversies arise when conflicting views emerge regarding the problems, strategies, and solutions associated with the evolution of a given technology (Bijker, 1995). In the case of biotechnology, a public debate on the risks of its applications has been ongoing since the mid-1970s (Wade 1984), generating, in subsequent decades, a huge volume of research on the controversies associated with its use, especially in the agri-food sector (Bauer 2005; Evanega et al. 2022; Nisbet & Huge 2006; Priest 1995).

However, few studies have focused on the perceptions of scientists in the field regarding the risks of different biotechnologies. This is particularly evident in the case of more recent subdisciplines and developments, such as synthetic biology, an area in which there are few publications addressing the issue (DeFrancesco 2021; Epstein & Vermeire 2016; Jin et al. 2021; Marris 2015; Rohden et al. 2022).

Understanding perceptions in the context of biotechnology research is key in two areas. On the one hand, it allows us to explore the ways in which risk is processed in cutting-edge or emerging techno-scientific fields. Second, the challenge of addressing the risks of emerging technologies, regulating their development, and establishing frameworks for their governance not only requires clarity regarding these potential risks, but also knowledge of the narratives of the actors and institutions involved in the field and capable of acting on it (Bauer & Bogner 2020; Marris et al. 2014; Vallejos-Romero & Garrido 2019; van Baalen et al. 2023).

In light of this, the systematic review was guided by the question: What is the perception of researchers in the field of biotechnology regarding the risks of the technologies developed in their field?

The generation of scientific knowledge and risk as controversy

Over the last few decades, biotechnology has been one of the most controversial techno-scientific fields due to the risks perceived by the public. These controversies are social processes, and to understand them, two elements must be taken into account: (1) the way in which science, understood as a social system or institution, generates knowledge, and (2) the dynamics that lead to the emergence of disagreements within scientific fields or to the questioning of scientific facts by actors outside the field (political actors, the general public, or interest groups of some kind).

From the perspective of classical sociology of science, it is postulated that scientific knowledge is generated in the activity of a community organized in a democratic social structure, that is, that the members of that community carry out their research and collaborate, always prioritizing the common goal of achieving advances in science (Merton 2002). However, this perspective has been the target of profound criticism because, although it constitutes an ideal type of science as an institution or social system useful for analyzing the scientific ethos, it does not correspond to the reality of the operation of science and the multiplicity of interests that motivate scientists (Bourdieu 1994, 2008; Knorr-Cetina 1996; Latour & Woolgar 1995).

One of the first challenges to the traditional view of scientific activity comes from the analysis of the social structure of scientific revolutions. According to this view, science usually operates under conditions of normal science, that is, guided by a paradigm that generates consensus in the community (Kuhn 2013). However, at certain junctures, the prevailing paradigm is unable to respond to certain problems, thus initiating a scientific revolution in which competing paradigms are confronted in a process involving scientific and social aspects (Kuhn 2013).

Later, Latour & Woolgar (1995), based on an ethnographic study of a laboratory, would radicalize this approach to science as a social process. According to their thesis, scientific facts are not discovered, but rather constructed through complex social processes involving negotiation, interpretation, and consensus building in a given scientific field (Latour & Woolgar 1995).

This is not the only current that rejects the idea of the neutrality of the construction of scientific facts. In a similar vein, Knorr-Cetina (1999) examines the scientific laboratory as a space in which, simultaneously, nature

is reconstructed into the object of study and the scientist is constructed as the counterpart of this object, a process that unfolds under a given epistemic culture—that is, a set of practices, mechanisms, and arrangements that, taken together, orient the generation of scientific knowledge within a field.

From the above, it follows that there is currently a certain consensus that the generation of scientific knowledge is not linear. On the contrary, it is conceived as a complex process mediated by conflicts and tensions between the purpose of science as an institution—that is, to achieve knowledge that provides more satisfactory explanations for the problems that are relevant to it at a given moment—epistemic cultures, and the personal interests of scientists.

Due to the crucial role of disagreements and debates in the process of scientific knowledge generation, socio-technical controversies have become a highly researched problem in the field of social studies of science and technology. These dynamics can become crucial junctures for driving scientific revolutions. However, there are various approaches to this phenomenon, each problematizing in different ways the way in which controversies emerge and are resolved.

Kuhn (2013) suggests that, when faced with anomalies that cannot be resolved within the current paradigm, alternatives generate a process of debate and controversy in which the relevance in the field and the networks of influence of the scientists who support each paradigm in dispute will be crucial factors. In this early perspective on science and the activity of scientists, the relevance of social factors in the development and resolution of techno-scientific disputes can already be observed.

Latour (1987), one of the most influential authors in the field of socio-technical controversies, broadens the understanding of controversies by not limiting the social processes that give rise to them to the realm of science. For him, these types of controversies emerge when the black box of science is scrutinized. That is, the set of debates and procedures that led to the acceptance of a scientific fact that has come to be considered true or to the relative consensus regarding the design of a technological device (Latour 1987). In principle, the actors who can open the black box associated with a certain scientific fact or technological development do not necessarily have to be scientists.

Callon et al. (2009), meanwhile, suggest that controversies arise in contexts of technical uncertainty, that is, when there is no single position on a socio-technical topic. In this framework, hybrid forums are created, that is, open spaces where interest groups of various kinds discuss technical options. According to the authors, this responds to a shift in democracy from representative to dialogical, a transition that implies the democratization of science and technology (Callon et al. 2009).

Similarly, Bijker (1995) argues that controversies arise when there is interpretative flexibility regarding a socio-technical device, that is, when different technological frame or points of view coexist on a given technological object. These points of view are defended by different relevant social groups, which seek to resolve the controversy with a solution that is as close as possible to their own perspective.

In this context, Bijker (1995) adopts a constructivist stance, in which society determines technological change. This thesis contrasts sharply with the traditional Marxist postulate, according to which the relationship between technology and society has the opposite direction: it is technology that determines the type of society, and not the other way around (Heilbroner 2009). However, for Heilbroner (2009), the latter perspective becomes untenable in the context of a modern capitalist society, which is characterized by having unleashed the forces of technological change.

Methods

Selected search engines

This study has used the Web of Science, Scopus, and Dimensions scientific article databases for its search. Web of Science and Scopus are the scientific databases with the longest tradition, offering extensive coverage of journals in different areas of knowledge (Chadegani et al. 2013; Harzing 2019; Singh et al. 2021). Dimensions, on the other hand, is a recently created database that aims to challenge the dominant position of Web of Science and Scopus (Harzing 2019; Singh et al. 2021; Thelwall 2018).

One of the most relevant differences between these publication databases is related to the spectrum of journals they cover. Web of Science and Scopus place a strong emphasis on the fields of natural sciences, engineering, and biomedicine, while Dimensions has sought to become a platform with broad coverage of social sciences and humanities (Singh et al. 2021). Likewise, the thresholds established to define which journals are indexable differ in each case: Web of Science maintains very strict and, therefore, highly exclusionary criteria, while Dimensions applies more lenient criteria in order to capture the largest possible volume of relevant literature (Stahlschmidt & Stephen 2022).

It should be noted that global scientific publication databases have a clear linguistic bias, primarily considering works written in English (Tennant 2020), which may mean excluding relevant works written in other languages. However, publications written in languages other than English and indexed in these databases also pose a challenge for conducting systematic searches.

Indeed, although most works include an abstract in English, translating all potentially relevant articles may not be feasible given the resources available to researchers. In this case, one alternative is to exclude documents written in languages that researchers do not speak, noting how many and which ones, so that in the future, other researchers who do speak those languages can access those publications (Gough et al. 2012).

Search command

The search for publications was limited to a time frame covering the last two decades. This decision is based on the fact that during this period numerous developments in the field of biotechnology consolidated and emerged, while, at the same time, several protest movements against the advancement of these types of technologies and their application in industries such as the agri-food sector began to (re)emerge.

We began by conducting an initial exploratory search, which considered only the terms "*risk*," "biotech*," and *"researcher*," as these were the key concepts of the defined question. The search considered the title, abstract, and keyword fields, thus covering the textual content that all publications usually have in open access. Thus, the search command for this first exploratory approach was formed as follows:

TITLE-ABS-KEY(researcher AND biotech* AND risk) AND PUBYEAR > 2003

This first search yielded 306 results in Scopus. The search command was supplemented with the most recurrent indexing keywords in this set of documents and the incorporation of synonyms and terms related to those already considered. In addition, the concept of "perception" and related terms were considered in order to increase the specificity of the results obtained. This led to a second search string, which yielded 125 results in the same database. This process was repeated four more times in order to obtain a search string that balanced sensitivity and specificity.

In general terms, systematic reviews must strike a balance between sensitivity and specificity—since these are inversely proportional properties—with one alternative to increase sensitivity being the inclusion of multiple terms and the consideration of several publication databases in the search (Petticrew & Roberts 2006). In light of this, and noting that the increase in results across the last three iterations of the search string was marginal, it was deemed appropriate to adopt the final version of the string as definitive. For Scopus, it was configured as follows:

> TITLE-ABS-KEY((((scientist OR researcher OR "scientific community" OR "research community" OR expert OR biotechnologist) AND (biotech* OR "synthetic biology" OR synbio OR "genetically modified" OR "gene* modification" OR gmo OR "genetically engineer*" OR "transgenesis" OR "transgenic" OR "genome editing" OR "gene editing" OR mutagen* OR crispr))) AND (risk OR danger OR threat OR peril OR hazard OR harm OR menace OR "dual use" OR safety OR biosafety OR uncertainty OR biosecurity) AND (attitude OR imaginary OR representation OR narrative OR discourse OR perception OR opinion OR view OR perspective OR stance)) AND PUBYEAR > 2003

Once the final search was performed in each database, the metadata from the publications was downloaded in order to consolidate a single database and facilitate the subsequent stages of the work.

Inclusion and exclusion criteria

The three searches yielded a total of 3,204 records. Based on the DOI data and titles, a total of 1,267 duplicates were eliminated, reducing the set of documents to 1,937.

After this initial data cleansing, the articles were scrutinized in order to select the works to be analyzed in the next phase of scrutiny. In this procedure, special attention was paid to the metadata linked to the language of the article and the type of document, in addition to the titles and abstracts.

The inclusion criterion was that the publications had as their main objective to report on the perception of the risks of biotechnology among researchers in the field. Meanwhile, the first exclusion criterion was that the documents corresponded to a type of document other than articles, reviews, chapters, or conference papers,

since these documents present the most relevant results. Finally, in order to ensure the feasibility of the review, documents that were not written in English or Spanish were excluded.

Results obtained and sample constructed

Of the 1,937 unique records identified, 260 were discarded because they did not correspond to the types of documents of interest for this review. Likewise, 76 publications written in a language other than English or Spanish were excluded. As a result, a set of 1,601 documents was selected for the title and abstract scanning stage. After this initial analysis, it was found that only 40 papers met the inclusion criteria.

Subsequently, a second scanning phase was carried out, in which the documents selected in the previous stage were read in their entirety. This procedure led to the exclusion of fifteen publications: three because the full document could not be accessed, four because they did not present data on risk perception, and eight because they considered more actors in their samples and the presentation of results did not allow the responses of scientists to be distinguished from those provided by other groups.

Thus, 25 publications were considered for the systematic review. The search and selection process is outlined in Figure 1 below.

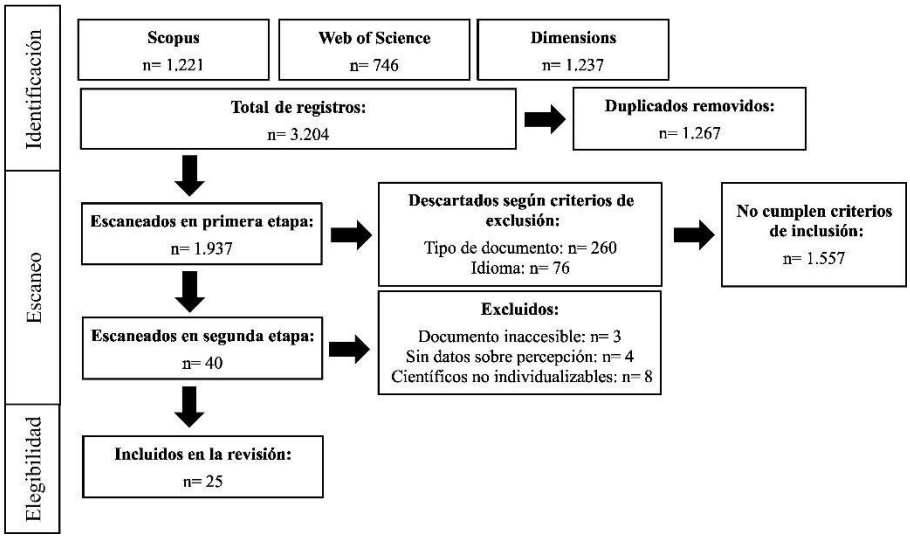

Figure 1. Results of the search and sampling process. Source: Authors' own work.

Results

The articles included in the review are distributed fairly evenly across the defined time range. Most of the reported research was conducted in the United States, the European Union, and Japan. Methodologically, quantitative techniques predominate, as most of the studies rely on surveys as their main data collection mechanism.

The results reported regarding scientists' perspectives on the risks of biotechnology are generally similar across the different studies. However, there are interesting differences in the approach to the problem. The review has identified three ways of approaching the problem, namely: (1) focusing solely on scientists' perspectives on the risks of biotechnology, (2) analyzing the differences in risk perception between scientists and the general public, or (3) delving deeper into scientists' perspectives on the validity of the public as a stakeholder in the debate.

The following sections present the main results of research addressing scientists' perceptions of biotechnology. The Appendix includes a more detailed description of the context studied in each publication, the methodological approach, the sample, and the main results.

Scientists' perspective on the risks of biotechnology

Regarding scientists' perspectives on the risks of biotechnology, studies tend to focus on the food domain, especially genetically modified crops. In this line, various studies show that virtually all scientists in this field consider that there are no risks associated with these foods, whether in relation to human health (Huang et al. 2017; Kangmennang et al. 2016; Katto-Nita et al. 2019; Lassoued et al. 2019; Pappalardo et al. 2021; Ray & Rampal 2018; Sjöberg 2008), the economy (Lassoued et al. 2019), the environment (Kangmennang et al. 2016; Katto-Nita et al. 2019; Lassoued et al. 2019; Pappalardo et al. 2021), or society (Katto-Nita et al. 2019; Lassoued

et al. 2019). It is interesting to note that Aleksejeva (2014) reports that 50.7% of scientists consider that the risks of genetically modified crops for health and the environment should be studied on a case-by-case basis.

Using a methodological strategy based on the analysis of the language used in papers on genetically modified crops published between 2000 and 2018, Stevens et al. (2021) found that 40% of these publications take a non-neutral stance, with articles funded by private sources six times more likely to be positive.

A qualitative study focuses specifically on the case of genetic drivers. The study concludes that, although researchers acknowledge a certain level of uncertainty, they do not believe this is a sufficiently strong argument to halt testing of this technology outside the laboratory (de Graeff et al. 2021).

Some studies have compared perceived safety across biotechnology uses in food and medicine, finding that the vast majority of scientists consider applications in the latter field to be safer than those in the food domain (Inaba & Macer, 2004; Savadori et al. 2004). Inaba & Macer (2004) reveal that, for 85% of Japanese scientists, the safest applications are the production of medicines in genetically modified organisms and the development of mouse cancer models for research, while the riskiest application is xenotransplantation. Also in relation to medical uses, it has been reported that Japanese regenerative medicine researchers consider scientific validation and experts' capacity to manage risks and accidents to be key factors in the acceptability of advances in the field (Shineha et al. 2018).

Other, more recent studies have directed their attention toward the field of synthetic biology. From the perspective of Australian scientists, this field entails ecological risks derived from accidental or intentional releases of synthetic organisms; social risks, such as bioterrorism and biopiracy; and economic risks, insofar as the benefits of synthetic biology could generate or deepen inequalities within and between countries (Dalziell & Rogers, 2023). A different diagnosis is offered by Jin et al. (2021), showing that Chinese and European scientists do not perceive risks associated with this technology per se, although they acknowledge that it may cause harm if used by criminals or companies with an excessively profit-driven orientation. Meanwhile, Howell et al. (2020) observed differences in risk representations among U.S. scientists according to age and race, with younger and white scientists perceiving more risks in synthetic biology.

Thus, among scientists in the field, there is a prevailing epistemic culture that promotes a technological frame that minimizes the risks of biotechnology, especially in the case of applications with a longer history. However, scientists are more open to recognizing risks when it comes to recently developed technologies, such as those related to the field of synthetic biology. This implies that, despite the prevalence of the aforementioned epistemic culture, the novelty of such technologies leads some scientists to be more inclined to recognize a greater degree of uncertainty and, therefore, the possibility that there may be some associated risks.

Differences between scientists and the general public regarding perceived risks

Several studies explore the differences between the views of scientists and the general public regarding the risks of biotechnology in a specific geographical area. Many of these studies are purely comparative in nature and do not delve deeply into the perceptions of each of these groups. This category includes various publications that show that, in Italy, Sweden, and Japan, risk perception is much higher among the general public than among scientists, both in food applications (Inaba & Macer 2004; Kato-Nitta et al. 2019; Pappalardo et al. 2021; Savadori et al. 2004; Sjöberg 2008), as well as in medical applications (Savadori et al. 2004; Shineha et al. 2018).

For their part, Howell et al. (2020) focus their analysis on the influence of different demographic variables on the perception of risks of synthetic biology among experts and the general public. Their results show that age and race are characteristics that condition perception in both groups, while, among the public, conservative ideology and high religiosity lead to a higher assessment of the risks in this field.

Four studies approach the phenomenon of the difference in perceptions of the risks of biotechnologies between scientists and the lay public from a representational-epistemological perspective. Thus, studying the discourses of experts and the public regarding the risks of a vaccine for livestock made from artificial genes, Ditlevsen et al. (2020) find that the notion of *unnaturalness* appears repeatedly in the public discourse as an argument underlying the perception of high risks in this vaccine, a reality that is totally contrary to what occurs among experts, who do not use this concept and consider that there are fewer risks associated with the vaccine.

Similarly, research has been conducted on the mental models that structure the positions of experts and the general public regarding the risks of crops developed using biotechnological tools. In this regard, the different role that uncertainty plays in the logic of both groups stands out. Scientists consider the assessment of risks and benefits to be key, while the general public equates uncertainty about the effects of a particular application of biotechnology with the risks of that application (Hagemann & Scholderer 2007, 2009).

In a related line of research, the epistemic cultures that emerge among researchers and actors outside the field have been examined in the context of the debate on the risks of genetically modified organisms. It has been suggested that these different epistemic cultures differ in the way they process non-knowledge and evidence, which would be a critical point for the discussion on the regulation of the industrial use of biotechnology (Böschen 2009).

The findings of this set of studies show that the interpretive flexibility of biotechnology has been sustained throughout the 21st century. It is also apparent that the technological frame of scientists and the public who are reluctant to accept these technologies differ radically in the way they make sense of uncertainty and the application of the precautionary principle. Thus, while scientists tend to dismiss the potential risks of these technologies in light of their benefits, the opposing public judges the very existence of interpretive flexibility as an indication of risk.

Scientists' perspective on the public as an interlocutor in the debate and argumentative dynamics

The intensity of the public debate on the use of certain biotechnological advances in different industries, particularly those related to food, sparked interest in studying the extent to which scientists in related fields considered the lay public to be valid interlocutors. Thus, Cuppen et al. (2009) report that scientists are biased in their processing of public arguments, being particularly receptive to statements that coincide with their position and are expressed in a non-emotional manner. These results are consistent with those presented by So et al. (2023), which highlight the lack of reflexivity in scientists' positions regarding the debate on the possible risks of genetic editing in crops, as they tend to consider critical positions toward these technologies to be the product of public policymakers and uninformed citizens.

The analysis of the debate on policy regarding genetically modified organisms in Ghana, conducted by Kangmennaang et al. (2016), reveals that scientists respond to public questioning by resorting to counter-rhetorical dynamics that dismiss the interlocutor's allegations as isolated incidents, unfounded, insincere statements, or de-problematize them by hiding behind the emotional basis of the complaint. Meanwhile, in the Icelandic context, Hjörleifsson & Schei (2006) report that human genetics researchers, despite tending to dismiss public fear as irrational, recognize that there are some points on which skepticism could be justified, while acknowledging that, despite their specialized knowledge, they themselves often adopt a personal or ambiguous stance.

On the other hand, the function of certain discursive devices in the debate between scientists and the general public regarding the risks of biotechnology has also been studied. In this context, findings indicate that commonplaces (set phrases, clichés, popular sayings, etc.) often play an important interactional role, allowing disagreements to be mitigated, topics to be moved between, uncertainty to be processed, and moral codes of conduct to be negotiated (Lassen 2008).

Some studies have focused on the field of synthetic biology. The results of this research show that scientists who perceive greater risks associated with this group of biotechnologies consider that the general public can be a valuable actor in the debate and are more open to the implementation of more participatory governance systems (Wirz et al. 2023). Meanwhile, in China and the European Union, scientists have been found to underestimate the risks of synthetic biology, presenting scenarios in which the public rejects these technologies due to their irrationality and lack of knowledge on the subject (Jin et al. 2021).

Taken together, these studies show that, although in certain contexts there is openness to public debate and even to participatory governance models for biotechnology risks, scientists predominantly dismiss the technological frame of the general public. This constitutes a significant limitation to the favorable development of hybrid forums or participatory democratic debate on technological advances in the field of biotechnology.

Conclusions

The systematic review has identified a significant body of publications on the perceptions of scientists researching in the field of biotechnology regarding the risks associated with this field. Specifically, a total of 25 articles on the subject have been analyzed. Most of these address the agri-food applications of these technologies, but there are also a significant number of studies that focus on other areas.

It has been established that the research approaches the problem from three angles: (1) focusing solely on scientists' perspectives on the risks of biotechnology, (2) analyzing the differences in risk perception between scientists and the general public, or (3) delving into scientists' perspectives on the validity of the public as a stakeholder in the debate.

Regarding scientists' perspectives on the risks of biotechnology, in general terms, the evidence shows that most scientists believe that genetic modification does not pose significant risks (Huang et al. 2017;

Kangmennang et al. 2016; Kato-Nitta et al. 2019; Lassoued et al. 2019; Pappalardo et al. 2021; Ray & Rampal 2018; Shineha et al. 2018; Sjöberg 2008). However, in some cases, medical applications have been found to be considered less risky than food applications (Inaba & Macer, 2004; Savadori et al. 2004).

However, in subfields related to more recently developed biotechnologies, such as gene drives and synthetic biology, it is possible to find scientific discourse that recognizes potential risks, although there are differences regarding whether these risks arise from the nature of these developments themselves or from the possibility of malicious use (Dalziell & Rogers 2023; Jin et al. 2021; Shineha et al. 2018). Consequently, it can be argued that the dominant epistemic culture in the field of biotechnology promotes a technological frame that minimizes its risks.

Regarding the differences between the perceptions of experts and the general public, the results of various studies agree that the latter consider biotechnologies to be much riskier than scientists in the field (Ditlevsen et al. 2020; Inaba & Macer 2004; Kato-Nitta et al. 2019; Pappalardo et al. 2021; Savadori et al. 2004; Shineha et al. 2018; Sjöberg 2008). At the same time, disparities have been noted in the way both actors tend to process non-knowledge, uncertainty, and evidence (Böschen 2009; Hagemann & Scholderer 2007, 2009). Thus, it can be seen that interpretative flexibility regarding biotechnology has been maintained throughout the 21st century, keeping the controversies surrounding it open.

Finally, regarding scientists' perceptions of the general public in the context of the debate on the risks of the field, the data show that researchers usually dismiss the position of non-experts who distrust biotechnologies, describing them as irrational or lacking sufficient scientific knowledge (Cuppen et al. 2009; Jin et al. 2021; Kangmennang et al. 2016; So et al. 2023). This undoubtedly hinders public debate from taking place in conditions that would result in the resolution of controversies in a democratic and participatory manner. However, in certain cases, it has been observed that researchers who are more open to recognizing the possible unintended consequences of biotechnologies consider skepticism about the field to be reasonable and are open to mechanisms of regulation and governance (Hjörleifsson & Schei 2006; Wirz et al. 2023).

The results of this review contribute to systematizing the perceptions of risk held by scientists in the field of biotechnology across different contexts. In this sense, the review makes it possible to map the findings of research that has addressed how scientists construct the risks associated with their objects of study. It thus provides a synthesized picture of the interpretive frameworks that predominate within one of the most relevant social groups involved in socio-technical controversies over biotechnology.

It has been shown that, far from the traditional image of science as a cohesive community (Merton 2002), debates over the risks of biotechnologies reflect the socially constructed nature of science and scientific consensus (Knorr-Cetina 1996, 1999; Latour 1987; Latour & Woolgar 1995). In this regard, although there is a general tendency among researchers in the field to argue that the risks of biotechnology have been exaggerated in public debate, some recognize a degree of uncertainty regarding the potential unintended consequences of certain applications, particularly those that have emerged more recently.

This finding is consistent with the thesis that technoscientific controversies tend to arise in contexts of technical uncertainty (Callon et al. 2009). Under such conditions, the prerequisites for interpretive flexibility with respect to a given technology are created—that is, for the emergence of divergent viewpoints concerning a particular technological object (Bijker 1995).

The studies addressed interactions among the various relevant social groups in these controversies only to a limited extent, primarily reflecting scientists' perspectives and, to a lesser degree, those of the general public. Nevertheless, they show that interpretive flexibility surrounding biotechnology has persisted throughout the twenty-first century, while contrasting scientists' views with those of the public and highlighting that scientists frequently consider the public's technological frame as irrational or as the result of insufficient knowledge.

This way, the findings of this review provide insight into how interpretive flexibility is processed within a cutting-edge technoscientific field. More broadly, this analysis offers an overview of the attitudes and representations held by those engaged in biotechnological research with regard to uncertainty and potential unintended consequences, within the broader context of a late capitalist society in which risks are embedded in its structures and functional dynamics.

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Appendix: Summary of publications included in the systematic review

Publication	Predominant approach	Country	Method	Sample	Main results
Shineha et al. (2018)	Differences between scientists and the general public	Japan	Quantitative (Survey)	1,115 members of the Japanese Society for Regenerative Medicine / 2,160 general public	Researchers in regenerative medicine perceive scientific validation and the ability of experts to deal with risks and accidents as key factors in the acceptability of new technological applications in the field.
Stevens et al. (2021)	Scientists' perspective	International	Qualitative (Content analysis)	230 publications	40% of publications have a positive or negative stance toward genetically modified crops. Among privately funded publications, the positive stance tends to be more favorable.
Ray & Rampal (2018)	Scientists' perspective	India	Quantitative (Survey)	10 researchers from Punjab Agricultural University	Most researchers have a favorable stance on genetically modified crops, perceiving that they pose no risk to human health.
Cuppen et al. (2009)	Scientists' perspective on the general public	Netherlands	Quantitative (Survey)	73 scientists affiliated with Dutch universities or research centers	Scientists are biased when processing arguments from the general public, tending to accept those that coincide with their personal position and are presented in a non-emotional manner to a greater extent.
Lassen (2008)	Scientists' perspective on the general public	Denmark	Qualitative (Focus Groups)	Does not disclose the number of participants	In the debate on the risks of food biotechnologies, common ground plays a key role in the interaction between experts and the general public
Pappalardo et al. (2021)	Differences between	Italy	Quantitative (Survey)	258 members of the Italian Association of Agricultural	81% of agricultural scientists believe that genetically modified crops are safe for consumption, while only 54% of the

	scientists and the general public			Science Societies / 1,006 general public	general public agrees with this statement.
Hagemann & Scholderer (2007)	Differences between scientists and the general public	Denmark	Mixed (Delphi-Interviews)	24 experts from the Danish Institute for Food and Veterinary Research / 25 general public	There are considerable differences in the way scientists and the general public think about the risks of biotechnologies. The public equates uncertainty with risk, while scientists are less drastic in this regard.
Aleksejeva (2014)	Scientists' perspective	European Union	Quantitative (Survey)	67 experts from 23 European Union countries	50.7% of scientists believe that the health and environmental risks of genetically modified crops should be studied on a case-by-case basis.
Wirz et al. (2023)	Scientists' perspective on the general public	United States	Quantitative (Survey)	790 synthetic biology researchers	Scientists who perceive fewer risks in synthetic biology are more likely to defend scientific authority. Those who believe there are certain potential risks are more receptive to the perspective of the general public.
Savadori et al. (2004)	Differences between scientists and the general public	Italy	Quantitative (Survey)	58 biology professors or doctoral students / 58 general public	The general public perceives all biotechnology applications as riskier than scientists do. Scientists estimate lower risks in the medical field than in the food field.
Kato-Nitta et al. (2019)	Differences between scientists and the general public	Japan	Quantitative (Survey)	111 molecular biology experts / 3,000 general public	Molecular biology experts perceive fewer risks in genetic editing and modification technologies than the general public.
by Graeff et al. (2021)	Scientists' perspective	International	Qualitative	11 natural science experts	Researchers acknowledge some uncertainty related to the applications of gene drive technology, but do not consider this to be an argument for halting testing of this technology outside the laboratory.
Sjöberg (2008)	Differences between scientists and the general public	Sweden	Quantitative (Survey)	49 experts in genetic technologies / 469 general public	Experts have a favorable view of genetically modified foods, while the general public shows significant rejection.
Kangmennaang et al. (2016)	's perspective on the general public	Ghana	Qualitative (documentary analysis)	The number of documents analyzed is not disclosed	Scientists do not perceive any environmental or human health risks associated with genetically modified organisms. They usually respond to questions by dismissing them as unfounded or defusing them by focusing on the emotional basis of the complaint.
Hagemann & Scholderer (2009)	Differences between scientists and the general public	Denmark	Mixed (Delphi-Interviews)	24 experts from the Danish Institute for Food and Veterinary Research / 25 general public	Experts tend to define risks in terms of a cause associated with an effect. The general public, on the other hand, shows more abstract reasoning in which uncertainty is equivalent to risk.
Böschen (2009)	Differences between scientists and the general public	International	Qualitative (Interviews-Documentary analysis)	28 scientists (molecular biology, plant sciences, ecology, medicine).	There are different epistemic cultures in the debate on genetically modified organisms. These differ in the way they process evidence, non-knowledge, and uncertainty.
Inaba & Macer (2004)	Differences between scientists and the general public	Japan	Quantitative (Survey)	370 scientists / 377 general public	Scientists consider the production of medicines and the development of mice with cancer to be the safest applications of biotechnology. Meanwhile, the riskiest would be xenotransplantation.
Lassoued et al. (2019)	Scientists' perspective	International	Quantitative (Survey)	57 scientists	According to scientists, genetically edited crops pose marginal risks to the economy, human health, and the environment.
Hjörleifsson & Schei (2006)	Scientists' perspective on the general public	Iceland	Qualitative (Interviews)	13 researchers from the company deCODE genetics	While scientists are optimistic about the use of human genetics technologies for the prevention of

					common diseases, they acknowledge that there are areas where skepticism may be justified.
Huang et al. (2017)	Scientists' perspective	China	Quantitative (Survey)	806 scientists from agricultural universities and two national academies	Most scientists believe that consuming genetically modified crops does not pose a risk to human health.
Howell et al. (2020)	Differences between scientists and the general public	United States	Quantitative (Survey)	806 scientists / 3,145 general public	There are differences in the perception of risks of synthetic biology among US scientists based on their age and race, with younger and white scientists perceiving more risks in synthetic biology.
Jin et al. (2021)	Scientists' perspective on the general public	China/European Union	Quantitative (Survey)	9 Chinese researchers and 13 from the European Union	Chinese and European scientists do not perceive any risks associated with synthetic biology, although they indicate that damage could occur if it is used by criminals or if the pursuit of profit is exacerbated.
Ditlevsen et al. (2020)	Differences between scientists and the general public	Denmark, United Kingdom, Poland, Austria, and Spain	Qualitative (interviews-focus groups)	9 vaccine experts and 13 synthetic biology experts / 154 general public	The notion of naturalness is rarely used by scientists in the field of synthetic biology and vaccines. However, it is widely used among the general public, who perceive the unnaturalness of synthetic biology applications as a risk.
Dalziell & Rogers (2023)	Scientists' perspective	Australia	Qualitative	31 members of the Australian Research Council Centre of Excellence in Synthetic Biology	From the perspective of Australian scientists, synthetic biology presents potential ecological, social, and economic risks.
So et al. (2024)	Scientists' perspective on the general public	Netherlands	Qualitative (Interviews, diaries, digital media)	16 researchers in the field of plant sciences at Wageningen University	Scientists show little reflection on the potential risks of genetic editing in crops. They tend to attribute criticism to uninformed citizens and policymakers.