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Exploring diverse food system actor perspectives on gene editing: a systematic review of socio-cultural factors influencing acceptability

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Abstract

Despite the promise of new gene editing technologies (GETs) (e.g., CRISPR) in accelerating sustainable agri-food production, the social acceptability of these technologies remains unclear. Prior literature has primarily addressed the regulatory and economic issues impacting GETs ongoing acceptability, while little work has examined socio-cultural impacts despite evolving food policies and product commercialisation demanding input from various actors in the food system. Our systematic review across four databases addresses this gap by synthesising recent research on food system actors' perspectives to identify the key socio-cultural factors influencing GET acceptability. This review extends prior literature by including views from a more diverse range of actors (e.g., farmers and NGOs) and provides a better understanding of their perceived social benefits and concerns. We find food system actors perceive positive and negative impacts of using GETs in agriculture. These perspectives are often entangled in broader debates regarding sustainability and food systems issues (e.g., social justice). We discuss practical recommendations for policymakers, agri-food industry managers, and scientists to better align gene edited foods (GEFs) with food system actors' values. GEF policy, development, and commercialisation must reflect social values such as collective wellbeing and transparency to improve actors' acceptability. More research is required among marginalised food actors such as Indigenous and smallholder farmers.

Keywords Gene editing · CRISPR · Agri-food production · Food system actors · Acceptance · Socio-cultural factors

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Abbreviations

CRISPR-Cas9	Clustered regularly interspaced short palindromic repeats associated with protein Cas9
DNA	Deoxyribonucleic acid
GEFs	Gene edited foods
GETs	Gene editing technologies
GM	Genetic modification/genetically modified
WTP	Willingness to pay

Introduction

New gene editing technologies (GETs), particularly CRISPR-Cas9,[1] promise wide-ranging applications in agri-food production, including crop, livestock, and aquaculture

[1] New gene editing technologies (GETs) will be used in this article to cover a range of gene editing techniques, including clustered regularly interspaced short palindromic repeats associated with protein Cas9 (CRISPR-Cas9), three zinc-finger nucleases (ZFN-1, ZFN-3, and ZFN-3), and transcription activator-like nucleases (TALENS). CRISPR-Cas9 is now the dominant technology used to undertake gene editing of organisms and in this article is defined separately from genetic modification (GM).

breeding (Brandt and Barrangou 2019; Chen et al. 2019). These applications could offer powerful solutions for addressing challenges facing the agri-food industry and society (Karavolias et al. 2021; McClements et al. 2021). Specifically, scientists propose that GETs can achieve sustainable food system outcomes by making rapid and precise changes (e.g., insertions and deletions) to the deoxyribonucleic acid (DNA) of organisms (Chen et al. 2019).

While the process of selecting desirable genetic traits (e.g., high yielding) is not novel, the newfound precision and efficiency of GETs boasts rapid design of products with improved quality, increased nutritional value, climate resilience, and reduced pesticide use (Brandt and Barrangou 2019; Karavolias et al. 2021). As an example, the gene editing of seeds is predicted to increase farmer income by $100 billion annually and reduce micronutrient deficiency in 100 million people (McClements et al. 2021). Such transformations are critical as the growing global population requires healthy foods from a production system that does not perpetuate climate change and environmental degradation (McGreevy et al. 2022; Rockström et al. 2020).

Despite the "promise" of these technologies, there are also concerns regarding their desirability in agri-food production and potential impacts on actors in the food system (Helliwell et al. 2019; Jordan et al. 2022; Selfa et al. 2021), including uncertainty regarding risk and benefit trade-offs (Jordan et al. 2022; Lassoued et al. 2019a, b; Lassoued et al. 2019a, b; Nair et al. 2022). Understanding the conditions under which food system actors—a network of scientists, farmers, food manufacturers, retailers, NGOs, policymakers, and consumers (Caiazza et al. 2014)—view these technologies as acceptable remains unclear (Araki and Ishii 2015; Bartkowski et al. 2018; Scheufele et al. 2021; Spök et al. 2022).

Compared to the vast amount of literature exploring genetically modified (GM) food, robust empirical research on GET acceptability among food system actors is still emerging, albeit rapidly (Beghin and Gustafson 2021; Ferrari 2022; Nair et al. 2022). So far, literature in this area has primarily focused on reviewing the regulatory (Friedrichs et al. 2019; Mbaya et al. 2022; Spök et al. 2022) and socio-economic factors influencing technology acceptance and uptake (Lemarié and Marette 2022), including consumer attitudes and willingness to pay (WTP) (Beghin and Gustafson 2021). While such studies provide valuable insights into potential GET uptake, little is known about the wider socio-cultural factors influencing GET acceptability. Further knowledge of food system actors', defined as parties directly or indirectly involved in food chain activities, perspectives are needed to better understand the underlying processes influencing acceptability.

GETs acceptability is a dynamic and multi-dimensional concept comprising political, legal, social, cultural, and economic aspects (Spök et al. 2022; Wüstenhagen et al. 2007). We use the term acceptability to signify that it is an ongoing process and that acceptability, in contrast to acceptance, is not only an act of individuals and groups, but can also be built into the fabric of a technology (Fischer and Van Loo 2021). Further, as gene edited foods (GEFs) remain limited in the marketplace, we view acceptability as the psychological conditions under which a certain object is accepted, or at the very least tolerated by actors, rather than the extent of its uptake. In this review, we focus specifically on the social and cultural (socio-cultural) aspects of acceptability which included food system actors' perspectives (e.g., perceptions) toward GETs and GEFs, rather than other socio-cultural characteristics (e.g., demographics). Social factors encompass beliefs, perceptions, preferences, and attitudes all of which are shaped by cultural influences, defined as collective knowledge and behaviours (Thornton et al. 2011). While this review does not analyse the economic and political aspects of acceptability, we acknowledge these aspects are highly interconnected and are interested in how exposure to political systems and levels of economic development influence socio-cultural aspects.

Establishing this knowledge is essential given that socio-cultural contexts influence how technological issues are framed, debated, and adapted (Clapp and Ruder 2020). Further, several calls have been made to understand and include socio-cultural considerations alongside scientific risk and economic analysis in debates regarding GEFs (Bartkowski et al. 2018; Kjeldaas et al. 2022; Myskja and Myhr 2020). Such calls are unsurprising given strong opposition regarding GM food is grounded in social issues, such as unnaturalness and the perpetuation of industrial agriculture (Dürnberger 2019). Although, little is known about these issues regarding GETs, particularly as legitimate objections continue to be dismissed as irrational (Nawaz and Satterfield 2022b). We argue that further knowledge of GETs socio-cultural impacts is urgently required to better inform GET policy, product development, and discourse (e.g., trade press and mainstream media) to align these technologies with food system actors' values.

Therefore, the purpose of this paper is to explore the socio-cultural factors influencing GET acceptability. Two research questions guided the review: 1) what socio-cultural benefits and concerns are associated with using GETs in agri-food production? and 2) how do these socio-cultural factors influence the acceptability of GETs among food system actors? The scope of this review does not limit itself to one geographic area and includes studies that investigate GETs in the context of both crop and livestock products. Further, the systematic search involved science, social science, and business databases. This broad approach was chosen because of the emerging nature of research exploring the socio-cultural impacts of GETs (Bartkowski et al. 2018; Myskja and Myhr 2020).

To investigate the research questions, we systematically reviewed the literature on food system actors' perspectives regarding GETs and GEFs. By synthesising insights, we identify benefits and concerns and establish new insights on socio-cultural factors influencing GET acceptability, extending Lemarie and Marette's (2022) work on economic factors. This review contributes a new understanding of how socio-cultural factors influence food system actors' acceptability of GETs and seeks to fill the incomplete dialogue on GEFs social impacts. Such knowledge is essential as GEFs inch closer to the marketplace (Brandt and Barrangou 2019; Karavolias et al. 2021) and GET policies are reconsidered across the globe (Friedrichs et al. 2019; Mbaya et al. 2022). Additionally, rapid growth of research in this topic area necessitates an overview of rapidly evolving literature.

Importantly, this research also goes beyond solely focusing on consumers (Beghin and Gustafson 2021), and is the first paper to integrate the perspectives of eight diverse groups of food system actors. This unique approach allows us to develop novel insights as food systems are complex (McClements et al. 2021), and actors' perspectives are closely interrelated (Caiazza et al. 2014). By synthesising recent research on this topic from a novel multi-stakeholder angle, we expand and contrast knowledge on actors varying concerns and priorities, thus providing a clearer picture of how social acceptability has developed since GM food debates.

In practical terms, we reflect and provide recommendations that have important implications for policymakers, agri-food industry managers, and scientists on improving the social acceptability of GETs and GEFs. We also present four key socio-cultural factors to consider when developing GEFs and provide actionable recommendations and future research avenues under each factor to help shift GET development in line with food system actors' values based on their current perspectives. The following sections describe the methodology utilised to conduct the systematic review, data analysis, a discussion of the results, and finishes off with concluding remarks.

Methodology

The methodological approach of this research was guided by Petticrew and Roberts (2006), who describe systematic reviews as a method to identify, appraise, and synthesise relevant studies to answer particular research questions and make recommendations for future research. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al. 2021) were used to select relevant research articles. Following this, reflexive thematic analysis was employed within the bounds of the research questions to unearth patterns occurring within and across articles (Braun and Clarke 2012). We discuss limitations associated with this methodological approach in the limitations section of this paper.

Search strategy

The research questions guided the choice of search terms. To ensure the database searches would capture relevant articles, the search string was split into three components: the technologies (e.g., GETs), the area of technology application (e.g., agriculture, food production), and the perspective (e.g., attitudes, opinions, acceptance). The search string was systematically applied to four electronic databases: Scopus, Web of Science, FSTA (Food Science and Technology Abstracts), and Business Source Premier. See Table 4 in the online appendices for the search strings utilised in this review. The search was completed in mid- December 2022 (cut-off date 16th) and included studies published after 2010. The decision to restrict the publication date from 2010 to 2022 was appropriate because these technologies (e.g., CRISPR) were only proven feasible for agricultural applications after 2013 (Brandt and Barrangou 2019). Further, because of the complex and dynamic nature of socio-cultural factors, we sought to review the most up-to-date research in this area.

Screening and inclusion of articles

To summarise, a total of 2227 records were produced across four databases. Before the screening, articles were excluded if they were not published in English. Duplicate articles were removed, leaving 1603 articles to be screened by title and abstract. Conference papers/proceedings, thesis, reports, and books/chapters were excluded, leaving only peer-reviewed and indexed journal articles eligible for full-text screening. The criteria focused the search by excluding articles which involved (1) studies that solely explored GETs concerning humans or other environmental applications, e.g., human, and medical applications (gene therapy), or ecological applications (gene drives, conversation, and species protection), (2) studies that solely explored existing biotechnologies such as GM, transgenesis, and genetic engineering, and (3) studies that did not undertake primary data collection. Therefore, articles were included if they explored food system actors (e.g., farmers, scientists, policymakers, consumers) perspectives (e.g., perceptions, knowledge, attitudes, WTP, acceptance, and opinions) toward GETs and their potential use in agriculture and food production, including its resulting food products (crops and livestock). Zotero, a referencing software, was used to sort articles based on the inclusion and exclusion criteria, outlined in Table 5 of the

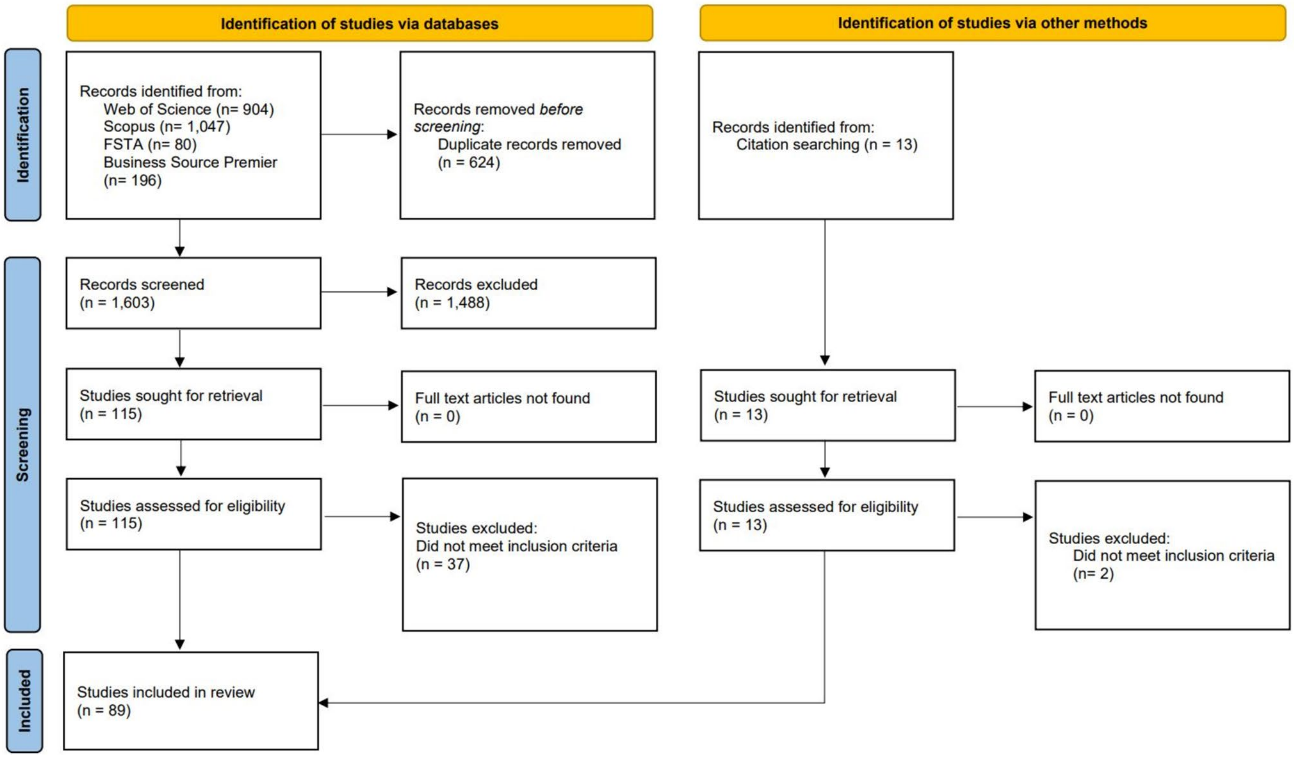

Fig. 1 PRISMA flowchart of the study selection processes of the systematic review, including identification, screening, and inclusion of relevant studies

online appendices. One hundred fifteen articles were sought for retrieval and were assessed for eligibility by a full-text screening to ensure they fit the scope of the review. Studies that fit the project's research questions were retained and included in the final review.

The records from each database search are displayed in Fig. 1. To ensure the full breadth of literature was evaluated, the review included papers with various models and methods (e.g., qualitative and quantitative). Further, studies that met the inclusion criteria were also used to identify other records via citation searching. Thirteen additional studies were assessed for eligibility based on the research questions. After the screening and selection process was completed by one researcher, 89 studies were included in the systematic review.

Data analysis

After a systematic approach was taken to capture relevant articles, a qualitative approach was utilised to analyse the data. As this review included studies from differing disciplines using diverse methodological approaches such heterogeneity can present challenges in comparing and synthesising results across studies. To manage this, a standardised data extraction process was taken to capture relevant information from all studies, that was attaching codes to sections of text data. In particular, reflexive thematic analysis was employed to identify patterns and themes within and across bodies of text (Braun and Clarke 2012). Reflexive thematic analysis is a qualitative method in which themes are conceptualised as meaning-based patterns as an output of coding. The aim of this six-phase approach (familiarisation, generating codes, constructing themes, reviewing themes, revising, and defining themes, producing the report) is to produce an interpretation of the data, grounded in the data (Braun and Clarke 2019). This approach has been shown to be useful in distilling insights from large bodies of work and has been used in similar applications (Wu et al. 2021). In an addition, the researchers used Microsoft Excel to produce descriptive statistics on the key characteristics of studies (e.g., country, journal) included in the review.

Each included study was analysed by one researcher in NVivo, a qualitative data analysis tool, and assigned content-related codes. Coding was conducted on a limited feature of the data set, in this instance all text under headings "results/discussion/conclusions". Groups of similar codes were later categorised into themes. Coding was completed by one researcher for consistency but could lead to individual coder biases. In order to manage this, theme development from the codes was conducted by four researchers through an iterative process. There was overall agreement on the coding and the emerging themes among all four authors. Codes were derived from extant literature (deductive) and emerged from the data (inductive). The data analysis was guided by the research questions and sought to identify socio-cultural benefits and concerns raised by eight food system actor groups, and how these may influence the acceptability of GETs and GEFs. The food system actor groups were also inductively determined, in other words, they emerged from the included studies and were then categorised into eight groups for simplification. While food system actors will not always be mutually exclusive in practice (e.g., Indigenous farmers) this inductive approach used the mutually exclusive classifications from each included study to categorise these actor groups.

Results and discussion

Study characteristics

Table 1 provides a brief overview of the key characteristics of studies included in the review, including the year of publication, journal title, countries in which data was collected, and data collection methodology. Of the 89 studies included, the majority were published between 2019 and 2022, testifying to strong, recent interest in GETs and GEFs. Further, 47 studies were published across a wide range of journals, demonstrating the cross-disciplinary nature of this topic. The journal titles in which most articles appeared are listed in Table 1. The remaining journals each published 1–2 relevant articles, and the orientation of journals was highly diverse: social sciences, environmental sciences, agricultural and biological sciences, and business management. This review also identified eight key food system actor groups explored in the literature. Of the 89 studies included, 67 explored a single food system actor group, while 22 studies addressed more than one actor. To investigate the proportion each actor group was studied overall, actors were treated as a single case (n = 135). A summary of actors and the percentage each was explored is shown in Fig. 2. A complete overview of the included studies is provided in Table 6 in the online appendices.

Actors perceived benefits and concerns of using GETs in agri-food production

This systematic review has synthesised and prioritised several socio-cultural factors. This was completed by grouping perceived benefits and concerns relating to the use of GETs in agri-food production as they were expressed by eight food system actor groups across 89 papers. To reduce the length of this paper we do not cite all articles at each opportunity. This analysis is summarised in Fig. 3. See Table 7 in the online appendices for a more in-depth summary of the perceived benefits and concerns of using GETs in agri-food production.

Socio-cultural factors influencing food system actor's acceptability of GETs and GEFs

We synthesised and thematically analysed the perceived benefits and concerns as a next step. We aimed to provide new insights in a parsimonious manner. As a result, we identified twelve dominant perceived benefits and concerns and condensed these into four key socio-cultural factors: *access and ownership, collective wellbeing, value-benefit alignment,* and *transparency* which are critical to the acceptability of GETs. The following sections will explain each factor, and Table 2 provides a summary.

Access and ownership

This review of food system actors' perspectives revealed that *access and ownership* is an important socio-cultural factor influencing the acceptability of GETs in agriculture. This factor is defined as how actors were concerned about access to these technologies (e.g., cost, regulation) and ownership of their resulting products (i.e., seeds). Specifically, we view access and ownership as distinct but related concepts. Access is the ability of groups to obtain and use resources, implying that restrictions might hinder some groups from benefits that are available to others, while ownership is possession or control over a specific asset or resource (tangible or intangible). This factor was represented through discussions about corporate power (i.e., the ability to influence decision-making regarding GETs), licensing, patents, and associated costs (i.e., technological or regulatory). In particular, actors often implied that access and ownership of GETs and their resulting products cause certain power dynamics, whether those are perceived as positive (i.e., used to achieve constructive goals) or negative (i.e., oppression of marginalised actors).

Scientists, plant breeders and biotechnology companies expressed that the acquisition of patents is vital for protecting innovation efforts and novel products (Middelveld and Macnaghten 2021). Patents generally protect GETs, their developments and agricultural applications, after which patent holders can define licensing strategies for new seed varieties or livestock applications (Lemarié and Marette 2022). Regarding access, scientists and industry actors view GETs as more accessible than GM (i.e., improved speed

Table 1 Key study characteristics of included studies

Study characteristic	Number of studies	Percentage (%)
Year of publication		
2010–2014	0	0%
2015–2018	8	9%
2019–2022	81	91%
Journal title *(journals with one or two articles are not listed)*		
Sustainability	8	10%
PLoS One	5	6%
Agriculture and Human Values	4	5%
Frontiers in Plant Science	4	5%
Elementa	3	4%
Food Quality and Preference	3	4%
Food Policy	3	4%
GM Crops & Food	3	4%
Journal of Agricultural Economics	3	4%
Transgenic Research	3	4%
Science, Technology, and Human Values	3	4%
Single versus multi-country studies		
Single-country focus	64	72%
Multi-country focus	25	28%
Country of data collection *(single and multi-country studies)*		
USA	26	20%
Canada	12	9%
UK	8	6%
Netherlands	8	6%
Italy	8	6%
Germany	7	6%
France	6	5%
Japan	6	5%
Belgium	5	4%
Australia	4	3%
Switzerland	3	2%
Brazil	3	2%
Sweden	2	2%
Spain	2	2%
Denmark	2	2%
Lithuania	2	2%
New Zealand	2	2%
China	2	2%
Costa Rica	1	1%
Malaysia	1	1%
Austria	1	1%
Philippines	1	1%
Latvia	1	1%
Romania	1	1%
Vietnam	1	1%
Madagascar	1	1%
Korea	1	1%
Chile	1	1%
Not specified	9	7%
Methodology		
Quantitative	61	69%

Table 1 (continued)

Study characteristic	Number of studies	Percentage (%)
Qualitative	20	22%
Mixed methods	8	9%

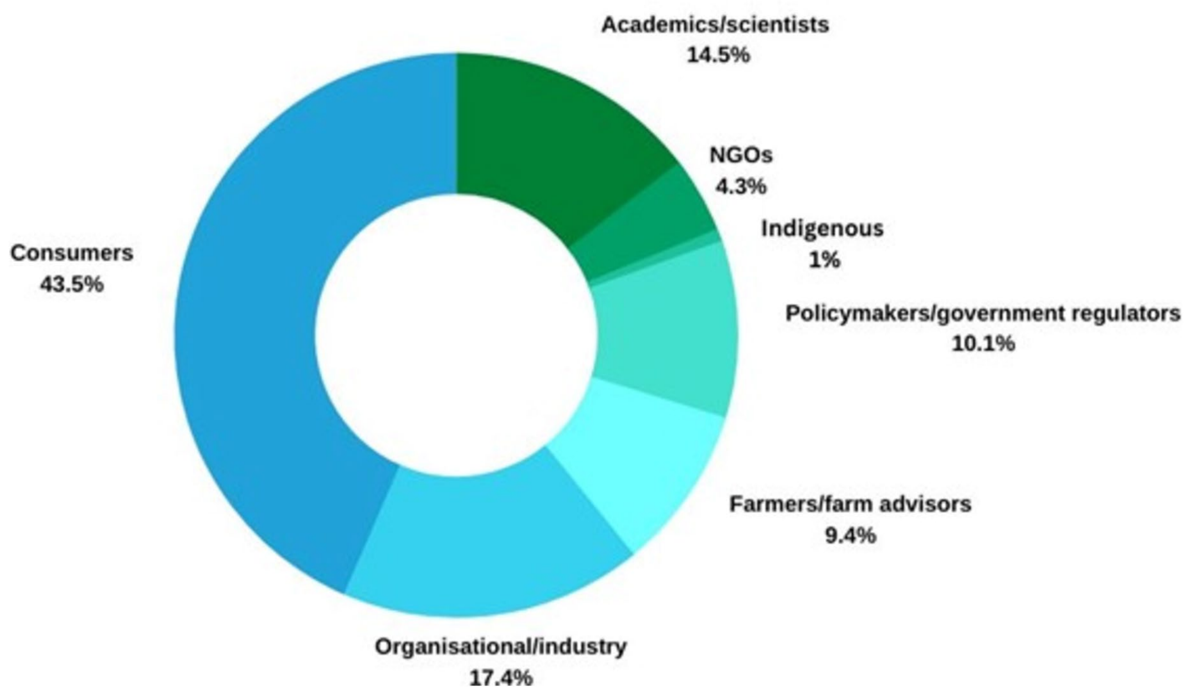

Fig. 2 Food system actor groups explored in the literature and the percentage each was explored within all reviewed articles. Actors were treated as a single case (n = 135). Consumers were the most researched actor group (43.5%), while NGOs (4.3%) and Indigenous (1%) were least researched

and ease of technology use) (Bain et al. 2020; Karavolias et al. 2021; Selfa et al. 2021). These groups suggested that technological improvements encouraged investment capital toward start-ups and away from large corporations, allowing smaller companies to also benefit from these technologies (Bain et al. 2020; Kang et al. 2022). However, in countries where following regulatory frameworks is costly, time-consuming, or difficult to navigate, smaller companies may lack the required resources to develop GEFs (Hallerman et al. 2022; Wesseler et al. 2019). Food system actors suggest these regulatory burdens may subsequently maintain the "status quo", and large companies, who have the resources to manage these issues, can benefit the most from using GETs (Hallerman et al. 2022; Kang et al. 2022; Wesseler et al. 2019).

Along a similar line, NGOs were generally critical of big corporations holding seed patents (Helliwell et al. 2019; Nawaz et al. 2020), which inadvertently or not, gives corporations utilitarian power based on material or financial resources. The rationale behind this concern is related to the reinforcement of corporate power, which consequently enables or expands food systems that undermine farmers' ability to control their seed supply and the impact of this on farming communities (Helliwell et al. 2019; Nawaz et al. 2020). Some farmers echoed this sentiment by discussing existing power dynamics in the marketplace (Barrett and Rose 2022; Jordan et al. 2022), that might obstruct their access to beneficial traits gained through GETs (Hallerman et al. 2022). In particular, farmers feared patents on GET seeds could promote monopoly situations and restrict their ability to reuse seeds (Maaß et al. 2019), raising questions about which farmers can afford GET seeds or who might be denied access to them (Jordan et al. 2022). These are valid concerns considering corporate practices relating to patents have required farmers to purchase new seeds each year and were a contributing factor to GM rejection in the past (Fischer et al. 2015).

On the demand side, consumers oppose GETs if they perceive these as maintaining highly industrialised or corporate forms of agriculture (Nawaz and Satterfield 2022a; Yunes et al. 2021). These concerns were most prevalent in discussions regarding animal agriculture as consumers believed financial interests primarily motivated these types of organisations to use GETs (Naab et al. 2021). Such findings

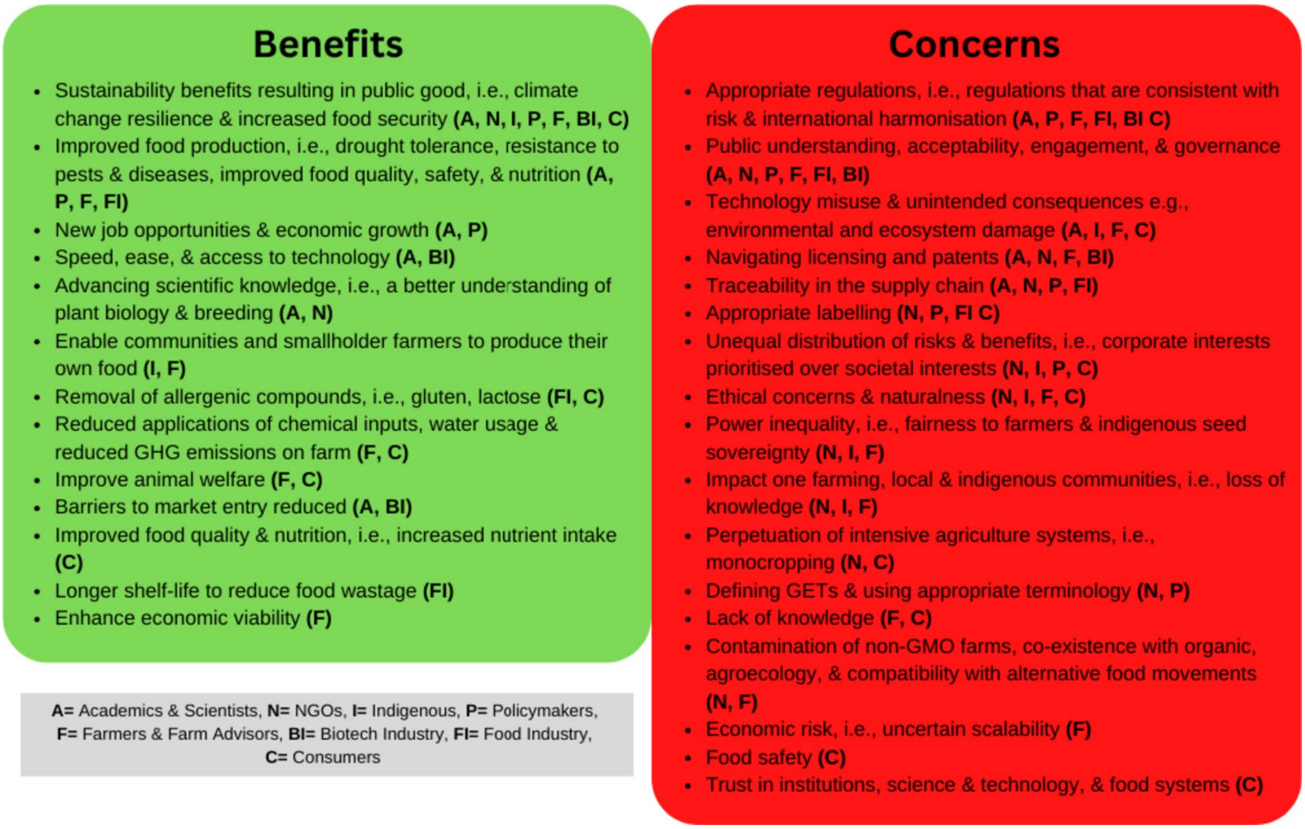

Fig. 3 Food system actor groups perceived benefits and concerns of using GETs in agri-food production synthesised from Table 7. These perceptions are listed from most dominant to least dominant across all the actor groups. Dominance was determined by how many actor groups discussed each benefit or concern across the articles, for example, seven actor groups discussed sustainability benefits (e.g., climate change resilience). The actor group is acknowledged and abbreviated accordingly beside each perception

suggest consumers are uneasy about large organisations benefiting from GETs. This trend may continue if larger companies acquire start-ups should GEFs become highly profitable (Clapp and Ruder 2020; Selfa et al. 2021). For instance, Bayer recently bought a majority stake in CoverCress, a cover crop start-up (Marston 2022). However, the current patent landscape of GETs is promising compared to GM, as many applications exist and these are held by multiple organisations of different sizes (Lemarié and Marette 2022).

Based on these findings, it is apparent that food system actors, including consumers, are highly conscious of who has "power" and consequently access to GETs. Thus, lasting impressions about GM access and ownership, and current food system power dynamics influence ongoing acceptability. To better align GETs with food system actors' expectations or concerns relating to access and ownership, we provide several recommendations to policymakers and industry in Table 3.

Collective wellbeing

Closely related to access is *collective wellbeing*, another socio-cultural factor influencing food system actors' acceptability of GETs. We view the notion of collective wellbeing as the prosperity of communities rather than focusing on the individual, with a particular emphasis on equity and inclusivity. In this specific context, collective wellbeing is characterised by hope exhibited among some actors regarding materialising the potential sustainability (e.g., climate change resilience) and social (e.g., equitable access) benefits of GETs. However, concerns were also raised regarding the equal distribution of these benefits, particularly among marginalised food system actors such as Indigenous communities.

The acceptability of GEFs varies based on whether consumers perceive a specific application as beneficial (Bearth et al. 2022). Specifically, some consumers are willing to pay more for GEFs that positively impact their own wellbeing (i.e., consuming foods with increased nutritional value) (Muringai et al. 2020; Vindigni et al. 2022), while others are more willing to accept applications with wider

Table 2 Socio-cultural factors influencing food system actor's acceptability of GETs and GEFs

Key socio-cultural factors	Summary of factor *Bold font and number in bracket (1 to 12) indicates the dominant perceived benefits and concerns synthesised from Fig. 3 and Table 7
Access and ownership	Describes tensions surrounding access and ownership. Scientists and industry actors view GETs as more accessible than GM (**i.e., improved speed and ease of technology use* (1)**). However, NGOs and farmers perceived **corporate power (2) and market structures (i.e., patents) (3)** as factors which can prohibit ownership. Lasting impressions about GM access and ownership, and current food system power dynamics influence the acceptability of GETs. The perceived benefits and concerns that comprise this factor were commonly discussed by industry, NGOs, and farmers
Collective wellbeing	Describes hope exhibited by actors', particularly academics/scientists, regarding materialising the **potential sustainability benefits of GETs (e.g., climate resilience (4)).** However, concerns were also raised regarding the **fair distribution of these benefits (5)**, particularly among marginalised food system actors (e.g., Indigenous groups). A wider range of actors must be included in dialogue to ensure equitable outcomes and improved acceptability. The perceived benefits and concerns that comprise this factor were commonly discussed by NGOs, Indigenous, and academics
Value-benefit alignment	Describes the need for holistic alignment between GET applications, their intended outcomes (particularly benefits), and food system actor values. Applications must be prioritised based on their **alignment with alternative food production techniques/systems (6)** and **suitability in local/national areas to reduce the impact on farming and marginalised communities (7).** Acknowledging and developing GETs according to non-market values **(e.g., ethical concerns & naturalness (8))** will improve acceptability. The perceived benefits and concerns that comprise this factor were commonly discussed by consumers, NGOs, and Indigenous actors
Transparency	Describes actors' desire for further information and oversight on GETs to mitigate feelings of uncertainty. Consumers and farmers **lack knowledge (9)** regarding GETs. More transparent business practices and regulations (e.g., **product traceability (10), labelling (11)**, and **public engagement (12)** are required to build trust and improve understanding and acceptability. The perceived benefits and concerns that comprise this factor were commonly discussed by consumers, policymakers, and industry

societal benefits (Cummings and Peters 2022a), for example, improved animal welfare (Gatica-Arias et al. 2019; Martin-Collado et al. 2022; Yunes et al. 2019), environmental sustainability (Naab et al. 2021; Shew et al. 2018), and reduced pesticide applications (Götz et al. 2022; Uddin et al. 2022). The type of benefits consumers prefer may be related to where they sit on the hierarchy-egalitarianism spectrum, namely, people with egalitarian worldviews opposed using GETs in agriculture as they believed these technologies promote social inequalities (Yang and Hobbs 2020b).

Similarly, farmers seemed acutely aware of the need for GETs to provide consumer and societal benefits, either above or alongside their own. While farmers are interested in GETs for economic benefit (Hallerman et al. 2022), they are also interested in varieties that can reduce environmental impact, breed disease resistance in animals and improve animal welfare (Maaß et al. 2019; Müller et al. 2022; Ufer et al. 2022b). Further, amidst increasing pressures facing farmers such as improving their environmental footprint, dealing with disease outbreak (Müller et al. 2022), maintaining competitive pricing (Robbins et al. 2021), and reducing pesticide or antibiotic use, they often viewed GETs as a hopeful solution for achieving these goals (Müller et al. 2022).

Despite these potential benefits, actors highlighted that GETs might favour the "already wealthy" or powerful, increasing inequalities felt by minority groups (Barrett and Rose 2022; Helliwell et al. 2019; Hudson et al. 2019; Yunes et al. 2019). Perspectives from minority groups, particularly Indigenous people, highlight that this is indeed a significant concern. In New Zealand, interviews with Māori stakeholders (the Indigenous people of Aotearoa New Zealand) highlighted a cultural concept called "Tika" (fairness). From a Māori worldview, tika would be diminished if the benefits of this technology and its products were only captured commercially, rather than shared equitably across the community (Hudson et al. 2019). Other settler colonial countries with Indigenous populations (e.g., Canada, USA, and Australia) require engagement to understand which applications may support or negatively impact these communities (Kathlene et al. 2022). From a public standpoint, arguments that GEFs predominantly boast farmer benefits may shift as GETs are used to develop products with broader societal impact (Brandt and Barrangou 2019; Karavolias et al. 2021). In a tangible example, Japanese start-up Sanatech released a nutritionally enriched tomato with GABA (a culturally significant nutrient) to support lower blood pressure (Mbaya et al. 2022).

These findings indicate GETs may be more acceptable if applications provide benefits equally to food system actor groups, as well as to wider society (Kuzma et al. 2016; Maaß et al. 2019). For example, GETs that provide societal benefits (e.g., climate resilience) rather than producer-only benefits should be prioritised (Jordan et al. 2022; Kaiser et al. 2021). While varying priorities among food system actors are likely to be observed, efforts to achieve win–win scenarios for all actors, including minority groups, must be contemplated. Refer to Table 3 for recommendations to align GETs with food system actors' expectations surrounding collective wellbeing.

Value-benefit alignment

The notion of value-benefit alignment can be defined as the alignment of values and benefits within a particular context. In this context, it involves the notion of holistically assessing the potential benefits of GETs against underlying food system actor values. Value-benefit alignment influences GET acceptability among food system actors, particularly perceptions of the need to use GETs in agriculture, and its compatibility with alternative food movements and local communities. These perceptions stem from actors' underlying values and ethics, demonstrating the need to acknowledge and include non-market values in debates regarding GETs.

While some individuals and groups may outrightly oppose GETs (Bearth et al. 2022; Yang and Hobbs 2020b), most actors, including consumers, have nuanced and heterogenous views (Beghin and Gustafson 2021; Jordan et al. 2022; Müller et al. 2022). Although consumers overwhelmingly prefer conventional breeding above GETs (Borrello et al. 2021; Marette et al. 2021; Martin-Collado et al. 2022; Muringai et al. 2020; Shew et al. 2018; Uddin et al. 2022; Ufer et al. 2022a; Yang and Hobbs 2020a, b), they acknowledged some applications might be necessary (Nawaz and Satterfield 2022a).

Consumer beliefs regarding the necessity of GETs may be linked to their sense of urgency towards climate change as a societal problem, but paradoxical results exist. For example, concern for the environment was associated with negative attitudes toward GETs, particularly loss of biodiversity (Ferrari et al. 2020) and intensive agricultural production, i.e., monocropping (Yunes et al. 2021). On the other hand, people who believed climate change was an urgent issue were more comfortable and supportive of GEFs (Nawaz and Satterfield 2022a). Thus, consumer acceptability seems to depend upon nuanced risk and benefit perceptions (Busch et al. 2022; Farid et al. 2020; Gatica-Arias et al. 2019; Shew et al. 2018; Yang and Hobbs 2020b). Mainly, GET applications were considered necessary only if no other changes could be implemented first to achieve the desired outcome (Yunes et al. 2021). Similarly, GETs were not desirable in circumstances that allowed agribusinesses to bypass rather than address problems through systemic change (Naab et al. 2021). These beliefs may reflect consumers' lack of trust in the food system (Nawaz and Satterfield 2022a; Vasquez et al. 2022; Yunes et al. 2021) or science and technology more generally (Cummings and Peters 2022a; Yang and Hobbs 2020a).

Further, personal ethics are a core driver in consumer willingness to avoid GEFs (Cummings and Peters 2022a; Uddin et al. 2022), particularly in livestock production (Naab et al. 2021; Vindigni et al. 2022). These ethical concerns may be associated with perceptions of naturalness, as some consumers view GETs as "unnatural" or tampering with the "laws of nature" given DNA is artificially altered (Debucquet et al. 2020; Naab et al. 2021; Yunes et al. 2021). In other words, not tampering with an organism's DNA maintains its integrity or purity (Nawaz and Satterfield 2022a). This so-called "natural-is-better-heuristic" may be inherently built into human preferences toward new food technologies (Siegrist et al. 2016). It may also be a characteristic of social and cultural relationships, suggesting the need for further exploration of the values embedded in perceptions of naturalness (Nawaz and Satterfield 2022b).

In contrast to consumer perspectives, plant breeders, biotechnology organisations, and scientists often portrayed a sense of urgency regarding technology uptake (Bain et al. 2020; Middelveld and Macnaghten 2021). Notably, the development of GEFs was a priority because they deliver desired outcomes faster than alternatives (e.g., conventional breeding and GM) (Lassoued et al. 2019a, b). With them, the challenges facing agri-food production were likely to be solved faster (Jordan et al. 2022). Thus, stakeholders were generally in agreement that GETs should be prioritised in instances where other viable solutions were not available, and applications should focus on issues most difficult to address using conventional approaches (Nair et al. 2022; Stetkiewicz et al. 2023). On the other hand, NGOs suggest that GEFs are only sometimes necessary, if at all, and that there are preferable alternatives for addressing agricultural issues (Helliwell et al. 2019). Further, other actors acknowledged possible issues regarding suitability in local or national contexts (Hudson et al. 2019), and compatibility with alternative food production techniques (Helliwell et al. 2019; Nawaz et al. 2020).

Based on these findings, food system actors are concerned about prioritising the use of GETs in agriculture, that is, assessing the relative need or urgency of choosing this technology over alternative methods. Generally, scientists believe that GETs are a useful tool for achieving sustainability goals in agri-food production (Bain et al. 2020; Kang et al. 2022). Thus, engaging in informed discussions about which applications are most necessary and considering how these align with market and non-market values, will assist in forming a consensus on which GET applications to develop. With this strategy, policymakers, scientists, and agri-food industry managers can determine which specific GET applications are desirable to majorities and which are not (Busch et al. 2022). We also suggest these strategies acknowledge values and ethical concerns as these are at the root of individual and group perceptions of GEFs. Table 3 provides suggestions for improving value-benefit alignment regarding the use of GETs in agri-food production.

Transparency

Transparency was a key socio-cultural factor influencing the acceptability of GETs and is defined as, conducting and communicating activities in a manner that enables others to easily observe the actions being performed. There are various elements to transparency but in this context, transparent practices may include actors right to know and choose GEFs (i.e., labelling), traceability, and public engagement activities. As consumers often mistrust the institutions managing these technologies, improving visibility and accessibility to information may be important mechanisms to rebuild trust.

A fundamental social concern lies in the inability to trace some organisms that have been altered using GETs (Helliwell et al. 2019; Jordan et al. 2022). Technological advances have enabled "nature-identical" organisms, defined as organisms created by GETs that leave no trace of any modification to genes (i.e., foreign DNA) and thus, could hypothetically be the result of conventional breeding (Bartkowski et al. 2018). These complexities impose challenges for actors in the food supply chain who wish to sell non-GEFs (Jordan et al. 2022; Maaß et al. 2019), such as organic food producers, because there is no simple test that can detect and identify these products (Nawaz et al. 2020).

From the demand side, NGOs saw nature-identical organisms as a major disruption to consumers' right to choose (Helliwell et al. 2019). While consumers did not specifically discuss the issue of traceability, they greatly expressed the need for GEFs to be labelled (Cummings and Peters 2022a; Ferrari et al. 2020; Vindigni et al. 2022). These findings suggest consumers desire the "right to know" whether food has been altered using GETs and saw product labelling as a means for making an informed decision. In contrast, industry and organisational actors often had mixed opinions regarding labelling (Selfa et al. 2021) and discussed the challenges associated with this requirement (Hallerman et al. 2022), particularly the additional costs that labelling incurs (Maaß et al. 2019; Wesseler et al. 2019). While some stakeholders opposed labelling for GEFs, stating it was unnecessary and misleading, others believed labelling improves transparency to consumers (Selfa et al. 2021). In particular, there were discussions regarding whether GEFs and GM foods should be labelled differently. Some retailers suggested distinguishing these two techniques would be difficult for consumers (Björnberg et al. 2015), which was partially supported by consumer research finding that GEF labels should differ from GM labelling but only if these were combined with education about the differences in techniques (Hu et al. 2022).

Consumer demand for GEF labelling may be linked to their limited knowledge (Cummings and Peters 2022a; Ferrari et al. 2020; Götz et al. 2022; Robbins et al. 2021; Vasquez et al. 2022; Vindigni et al. 2022; Yang and Hobbs 2020b; Yunes et al. 2019) and low awareness of GETs (Busch et al. 2022; Gatica-Arias et al. 2019; Kathlene et al. 2022; Nguyen et al. 2022). Based on this "knowledge deficit", a large majority of food system actors, including consumers, suggested more public discussion and information is needed on this topic. Scientists agree that educating the public about GETs, particularly communicating their benefits, is vital (Hallerman et al. 2022). NGOs also strongly support public discussion but emphasise educating to inform rather than to push technology acceptance (Bouchaut and Asveld 2020). In particular, these groups are critical of the technical language used by scientists to describe GETs because this makes informed debates difficult for lay audiences (Helliwell et al. 2019). Similarly, industry are concerned about the so-called disconnect between the image and reality of agriculture practices which limits constructive dialogue (Müller et al. 2022).

There are also mixed results on the impact of providing information to consumers on GEFs. For instance, consumers had more positive attitudes toward GETs or were willing to pay more for GEFs after being provided detailed information on the technologies risks and benefits (Farid et al. 2020; Marette et al. 2021; Nguyen et al. 2022; Ufer et al. 2022a). On the contrary, Naoko Kato-Nitta and colleagues (2019) found that providing consumers with information on GETs increased benefit perceptions but did not influence risk perceptions and resulted in more positive attitudes toward GE vegetables but did not change attitudes toward GE livestock (Kato-Nitta et al. 2021). The mixed impact of providing information may depend on consumers' trust in the institutions overseeing GETs (Cummings and Peters 2022b; Uddin et al. 2022). For instance, consumers supported GETs to reduce animal suffering but at the same time did not trust that these outcomes would eventuate, particularly under the control of large corporations or producers (Yunes et al. 2021). This lack of trust may be related to vested interests because consumers believed the industry was more likely to act with bias (Cummings and Peters 2022b), while information was more trustworthy from NGOs (Cummings and Peters 2022b), and governments (Farid et al. 2020).

Industry actors often view consumer hesitation as the most significant barrier to using GETs or selling their resulting products (Basinskiene and Seinauskiene 2021; Björnberg et al. 2015; Jordan et al. 2022; Maaß et al. 2019). This barrier was especially true for retailers who feared reputational damage (Maaß et al. 2019). Further, retailers implied that they face increasing pressures not to carry certain products, and that they are expected to drive change based on consumer priorities (Selfa et al. 2021). Despite these hesitations, many food system actors saw tremendous value in informing consumers about these technologies (Harikrishna et al. 2019; Jordan et al. 2022) and as a way to build trust and remove the stigma around these products (Selfa et al. 2021). These findings suggest that the use of GETs in agriculture and their acceptability among food system actors are shaped by the principle of transparency. Most notably, consumers must be able to make food choices in line with their values and avoid GEFs if they choose. Refer to Table 3 for recommendations on aligning GETs with actors' expectations regarding transparency.

Resetting the agenda

The following section presents a table of recommendations for aligning GETs with food system actors' values based on the key socio-cultural factors influencing their acceptability of GETs and GEFs. We outline how each factor can be considered and managed through recommendations to scientists, policymakers, and agri-food managers in Table 3. We reflect on our findings and draw on wider literature to provide these recommendations. Each factor (*access and ownership, collective wellbeing, value-benefit alignment*, and *transparency*) can be an enabler or disabler to the social acceptability of GETs but we position each factor in terms of improving food system actor acceptability. Some factors hold more importance to certain food system actor groups. Overall, each factor must be addressed simultaneously to encourage more holistic decision-making at a food-systems level. In the next sections, we briefly discuss our recommendations regarding each factor.

Regarding *access and ownership*, the act of making information and resources available to others without asserting exclusive ownership over them has been discussed as a solution for improving GET accessibility (i.e., open access, open

Table 3 Recommendations to align GETs with food system actors' values

Socio-cultural factor	Recommendations for scientists, policymakers, and industry
Access and ownership	Explore new business models to encourage entry from social enterprises, cooperatives & not-for-profits Consider alternative food economics, e.g., crowdfunding schemes & impact investing Consider alternatives to patents for instance, models of non-proprietary sharing (i.e., open access, open source, open data), patent pools, & waiving patent rights on non-commercial uses Consider non-exclusive licenses, compulsory licensing, & licenses mandating farmers can re-use seeds Ensure regulatory standards provide equal opportunity to small or public entities, i.e. funding or subsidies
Collective wellbeing	Consider equitable outcomes & sustainability requirements, i.e., sustainability assessments to measure the balance of social, economic, & environmental outcomes Consider local & regional conditions alongside global benchmarks Encourage collaborative discussions with marginalised actors, e.g., rural & Indigenous[a] Food system actors collaborate to find a common strategy that represents both market (private) & non-market (public) values Reestablish which social outcomes these technologies may address through problem identification & goal articulation with local communities
Value-benefit alignment	Consider prioritising the development of applications based on consumer acceptability, e.g., crop versus livestock & those delivering consumer, community, or societal benefit Encourage discussions about co-existence with alternative food systems, e.g., organic, agroecology Develop criteria for assessments in non-market values, i.e., measurable social impact, potential cultural risk, & prioritise development of GET applications using this information GET technology is chosen on the basis that it can (likely) contribute to meeting a pre-defined goal, and this is verifiable through measurement and greater utility than other technologies or practices[b] Respect & understand consumers' ethical concerns & naturalness perceptions, i.e., consider using Ethical Guidelines as an assessment tool[c] Consider GE-free labels as a values-based label for freedom of choice
Transparency	Establish consensus on GET terminology & definitions Provide information free from technical jargon & related to real-world applications Consider voluntary tracking & labelling schemes for traceability, i.e., the use of blockchain technologies in the supply chain Establish registries of GET applications in agri-food production Consider consumer education on food literacy, i.e., where food comes from & how it is produced Organise collaborative knowledge sharing on GETs & their use in agriculture, e.g., citizen juries, stakeholder workshops, & scenario workshops

[a]See Taitingfong and Ullah (2021) for suggestions regarding deliberative discussions with Indigenous communities

[b]See Heinemann and Hiscox (2021)

[c]See Antonsen and Dassler (2021) for an ethical assessment tool of gene edited organisms

data). Greater access may allow more actors to benefit by diversifying the types of crops and livestock modified by GETs (Montenegro de Wit 2020 2022). Further, this view of intellectual property rights may better align with groups (e.g., Indigenous peoples) who hold different worldviews to prevailing western notions of property (Kaiser et al. 2021). However, abandoning patents is not the only option as technology access is linked to how patents are used to exclude or invite (Kock 2021). Thus, solutions to distribute power more equally across the food value chain could focus on creating incentives to encourage alternatives to traditional patenting and licensing (Montenegro de Wit 2020, 2022), such as patent pools and non-exclusive licensing. For instance, one possible step forward is licensing that does not restrict farmers from reusing GET seeds. Additionally, the possibility of free or compulsory licensing, particularly for public good, remains an evolving discussion (Lemarié and Marette 2022). Aside from exploring alternatives to traditional intellectual property regimes, collaborative partnerships between food system actors could help to more fairly distribute potential GET seed ownership and alleviate existing power discrepancies (Montenegro de Wit 2022; Nlend Nkott and Temple 2021).

In terms of *collective wellbeing*, as marginalised groups tend to have their knowledge excluded we must invite new actors into discussions (Kennedy et al. 2022; Leeuwis et al. 2021) and shape food systems for the equitable distribution of benefits (Kennedy et al. 2022; McGreevy et al. 2022). Jordan et al. (2022) recommends co-constructing a scale on which individual GET applications are weighted on how they benefit food system actor groups. Further, global benchmarks should be considered alongside strategies for specific regions and contexts to develop crops and products of local importance (Kaiser et al. 2021; Taitingfong and Ullah 2021).

Regarding *value-benefit alignment,* interest in food products embedding social and ethical attributes is rising, but the current global food system often favors profit motives over non-market values (Kaiser et al. 2021), or dismisses these as irrational or emotional (Nawaz and Satterfield 2022b). While risk and economic assessments remain critical, decision-making must be rebalanced to include more values-based assessments that reflect actors priorities (Leeuwis et al. 2021). Prioritising the use GETs in agriculture based on these values may improve ongoing acceptability. This prioritisation should also consider "necessity" (Stetkiewicz et al. 2023), suitability in local or national contexts (Hudson et al. 2019), and possible co-existence with alternative food production techniques (Helliwell et al. 2019; Nawaz et al. 2020). Engaging in discussions about which GET applications are desirable and necessary to majorities and which are not, can inform technology development and commercialisation. We also acknowledge that optimizing acceptability among majorities may lead to compromises in equitable outcomes for some. Such tensions are not uncommon in debates regarding GETs (Nawaz et al. 2020; Selfa et al. 2021). Thus, the need for targeted policies and continuous assessment may work to balance both principles by addressing specific needs of minority groups while ensuring GET applications are acceptable more broadly.

When it comes to *transparency,* food system actors generally view public perception as the most significant barrier to using GETs in agri-food production (Basinskiene and Seinauskiene 2021; Björnberg et al. 2015; Jordan et al. 2022; Maaß et al. 2019). Thus, genuine engagement is needed between all food system actor groups, particularly between consumers and the organisations selling GEFs (Myskja and Myhr 2020; Scheufele et al. 2021). For example, this engagement could involve public and industry co-creating GEFs iteratively together whereby industry actively listens to consumer concerns and adjusts GEF products accordingly. At the same time, if certain actors wish to promote the benefits of GEFs, care must be taken to avoid portraying and promoting a single food solution (Kennedy et al. 2022) as GETs are no silver bullet. Further, to build trust and maintain ongoing acceptance, more transparent business practices are required. For example, the biotech industry may have the most demanding shift to undertake as these companies have reputations for disregarding social obligations (Leeuwis et al. 2021; Montenegro de Wit 2020). Jordan et al. (2022) suggest voluntary tracking and labelling schemes can ensure consumer choice and remedy dilemmas in countries where mandatory labelling is not currently required (e.g., the USA).

Limitations and future research directions

While systematic reviews such as this are a well-respected methodology, we also acknowledge some limitations of this study. Firstly, although extensive database and citation searching was conducted, the interdisciplinary nature of this topic means it is unlikely an exhaustive list of studies could be included, and relevant research may have been excluded. Further, non-English language articles were excluded from this review due to resource constraints, which may have provided deeper insights on perspectives from Indigenous populations. Secondly, our findings are based on limited studies concerning some food system actors and thus may not represent the views of the wider group. Thirdly, perspectives of GETs differ significantly between countries, regions, and cultures (Kato-Nitta et al. 2022; Spök et al. 2022). In particular, the perspectives analysed in this study were primarily collected in countries with advanced economies and therefore views from countries with developing economies are underrepresented. The two limitations above present important areas of future research. To better inform policy and improve equitable distribution of benefits, further research is needed in developing countries and among marginalised actors, such as Indigenous and peasant farming communities, who have had little input in GET discussions. A better understanding of their perspectives has clear merit for ensuring technological benefits and risks are fairly distributed (Feliú-Mójer 2020). Further, research could explore the possible tensions between equitable distribution of benefits and optimising acceptability among majorities.

Studies exploring food system actors' perspectives toward GETs necessarily provide definitions to participants given knowledge of GETs is low. Upon review of these studies in totality, inconsistent use of terminology to describe these technologies is observed and possible information framing effects are present (i.e., GETs being described as more precise (Bearth et al. 2022)). These information framing effects may be problematic when evaluating GET acceptability by creating biased responses (Spök et al. 2022), and also limit the comparability of results across studies. Future research might use more exploratory qualitative methods that evaluate knowledge and perceptions before, and after information about these technologies is provided. Additionally, researchers must strive to write up definitions regarding GETs that are standardized across studies and carefully considered to reduce information framing effects. This review also highlights three further opportunities for future research. Firstly, research is needed on GETs business models and patents, particularly how these influence ongoing acceptability. Secondly, crop breeding applications have been a major focus when it comes to understanding acceptance. Future studies could address other GET applications in the agriculture, e.g., aquaculture. Lastly, research should include organic, agroecologists, and regenerative farmers to establish views on co-existence with GETs.

Conclusion

If the promises of GEFs hold true, they could bring valuable sustainability outcomes to society (McClements et al. 2021). Against this backdrop, our systematic review identified four key socio-cultural factors critical to the acceptability of GETs. These factors are based on analysis across eight stakeholder groups, thus contributing new insights on the conditions under which these technologies may be more or less acceptable from a multi-stakeholder perspective. As the first paper to consider such a diverse range of food system actors, we broaden whose knowledge is considered of value in these discussions (Kjeldaas et al. 2022) and allow for a better understanding of the socio-cultural impacts of GETs and their use in agri-food production.

This systematic review uncovered that food system actors mostly want similar outcomes regarding GETs in agri-food production, particularly, prioritising collective wellbeing. Many food system actors were optimistic about the potential benefits of these technologies and saw GETs as one tool which could build climate resilience and greater food security in food systems. Such outcomes could have large-scale trickle-down effects for local economies, community development, employment, and human wellbeing (McClements et al. 2021). However, alongside these perceived benefits, actors also discussed corporate power, inequity, transparency, and the need for co-existence with alternative food movements. Thus, these views seem to reflect actors increased awareness of sustainability and the need for GET debates to encapsulate broader food system issues.

When comparing these findings to GM food debates, we observe that conversations have advanced. Industry and policy makers now use more holistic thinking and acknowledge the importance of building trust and establishing social acceptance. Nonetheless, further shifts among actors are required and public engagement efforts must increase, considering the public lacks knowledge of these technologies and trust in the food system. Further, decisions regarding GETs need to acknowledge and encompass local or regional considerations and reflect actors' values. For example, GETs could greatly benefit marginalised actors if more inclusive and collaborative discussions occur (Feliú-Mójer 2020; Taitingfong and Ullah 2021). These technologies may also be able to co-exist with alternative food production methods, assuming they can be freed from colonial-capitalist processes and values (Montenegro de Wit 2022).

We need to better understand food system actors priorities because taking a one-size-fits-all approach to using GETs is neither possible nor desirable, and the same could be said for global agri-food systems (Kaiser et al. 2021). There is no single food system or technology that can or should be imposed globally considering food underpins local cultures and livelihoods. We suggest there is space for those who champion post-growth paradigms (McGreevy et al. 2022) and those who champion more technology-oriented solutions (McClements et al. 2021). With this understanding, GETs development, policy, and commercialisation can become more aligned with food system actors' perspectives and values.

Appendix

For appendix see Tables 4, 5, 6, 7.

Table 4 Search string utilised to retrieve relevant articles

DATABASE	SEARCH STRING					FILTER
SCOPUS	("gene edit*") OR ("genome edit*") OR (CRISPR*) OR ("CRISPR-Cas9") OR (NPBT) OR ("new breeding technique*")	AND	(agriculture OR food*)	AND	(attitude*) OR (knowledge) OR (WTP) OR (acceptance) OR (perception*) OR (perspective*) OR (understanding) OR (willingness) OR (opinion*) OR (adopt*)	TITLE-ABS-KEY 2010–2022
WEB OF SCIENCE (Core Collection)	(gene editing) OR (genome editing) OR (CRISPR) OR (CRISPR-Cas9) OR (NPBT) OR (new breeding technique)	AND	(agriculture OR food)	AND	(attitude) OR (knowledge) OR (WTP) OR (acceptance) OR (perception) OR (opinion) OR (perspective) OR (understanding) OR (willingness) OR (adopt)	TS 2010–2022
BUSINESS SOURCE PREMIER	("gene edit*") OR ("genome edit*") OR (CRISPR*) OR ("CRISPR-Cas9") OR (NPBT) OR ("new breeding technique*")					2010–2022 "Academic Journals"
FSTA	Genome editing					SU 2010–2022

Table 5 Inclusion and exclusion criteria

Criteria	Inclusion criteria	Exclusion criteria
Criteria One	All retrieved articles must be published in English language	Any articles not published in English
Criteria Three	Peer-reviewed and indexed journal articles (employing both qualitative and quantitative methods) will be included in this review	Any books, chapters, proceedings, conference papers and reports
Criteria Four	Articles that explore food chain actors' (e.g., scientists, farmers, food processors, regulators, and consumers) evaluations (e.g., perceptions, knowledge, WTP) of CRISPR and its use (or potential use) in food production, including its resulting food products (crops and livestock)	1. Studies that solely explored GE in relation to humans or other environmental applications e.g., human GE and medical applications (gene therapy), or ecological applications (gene drives, conversation, and species protection) 2. Studies that solely explored existing biotechnologies such as GM, transgenesis, and genetic engineering 3. Studies that did not undertake primary data collection and analysis
Criteria Five	Provides insight related to the research questions e.g., articles exploring food system actors (e.g., famers, scientists, policymakers, consumers etc.) perspectives (e.g., evaluations such as perceptions, knowledge, attitudes, WTP, and opinions) toward GETs & their potential use in agri-food production	Not related to the research question

Table 6 Descriptive table from systematic review of food system actors' perspectives toward GETs and their use in agri-food production

Author & year	Application	Food system actor of interest	Sample size	Study design	Country where data was collected
(Bain et al. 2020)	Agriculture	Industry/organisational actors	30	Qualitative	USA
(Barrett and Rose 2022)	Agriculture	Farmers/farm advisors	15	Qualitative	UK
(Basinskiene and Seinauskiene 2021)	Food	Consumers, farmers, & industry/organisational	357	Quantitative	Lithuania
(Batalha et al. 2021)	Food	Consumers	114	Quantitative	Australia
(Bearth et al. 2022)	Tomatoes	Consumers	995	Quantitative	UK, Switzerland
(Björnberg et al. 2015)	Agriculture	Farmers/farm advisors & industry/organisational	5	Qualitative	Sweden
(Borrello et al. 2021)	Wine	Consumers	275	Quantitative	Italy
(Bouchaut and Asveld 2020)	Agriculture	Organisational/industry, government/policymakers & academia/scientists	34	Quantitative	Netherlands
(Britton and Tonsor 2019)	Cows	Consumers	3000	Quantitative	USA
(Busch et al. 2022)	Humans, crops, livestock	Consumers	3698	Quantitative	Canada, USA, Austria, Germany, Italy
(Calabrese et al. 2021)	Agriculture	Consumers, government/policymakers & academia/scientists	Not specified	Quantitative	USA
(Critchley et al. 2019)	Humans, crops, livestock	Consumers	1004	Quantitative	Australia
(Cummings and Peters 2022a)	Food	Consumers	2000	Quantitative	USA
(Cummings and Peters 2022b)	Food	Consumers	2000	Quantitative	USA
(De Jonge et al. 2022)	Agriculture	Smallholder farmers	N/A	Qualitative	Philippines
(de Lange et al. 2022)	Agriculture	Scientists	669	Quantitative	International
(De Marchi et al. 2019)	Apples	Consumers	582	Quantitative	Italy
(Debucquet et al. 2020)	Agriculture	Consumers	45	Qualitative	France
(Delwaide et al. 2015)	Rice	Consumers	3002	Quantitative	Belgium, France, Netherlands, Spain, UK
(Edenbrandt et al. 2018)	Bread	Consumers	713	Quantitative	Denmark
(Edenbrandt 2018)	Bread	Consumers	781	Quantitative	Denmark
(Farid et al. 2020)	Food	Consumers	718	Quantitative	Japan
(Ferrari et al. 2020)	Rice	Consumers	180	Quantitative	Italy
(Ferrari 2022)	Food	Farmers	143	Quantitative	Belgium, Netherlands
(Gatica-Arias et al. 2019)	Food	Consumers	234	Quantitative	Costa Rica
(Götz et al. 2022)	Tomatoes	Consumers	1018	Quantitative	Germany
(Hallerman et al. 2022)	Livestock	Organisational/industry, government/policymakers & academia/scientists	32	Qualitative	Brazil, USA
(Harikrishna et al. 2019)	Agriculture	Academia/scientists	457	Qualitative	Malaysia, Australia
(Helliwell et al. 2019)	Agriculture	NGOs	20	Qualitative	UK
(Hu et al. 2022)	Orange juice	Consumers	14	Quantitative	USA
(Hudson et al. 2019)	Humans, crops, livestock	Indigenous key informants	1096	Mixed Methods	NZ
(Jordan et al. 2022)	Crops	Farmers, farm advisors, NGOs, academia/scientists & organisational/industry	130	Qualitative	USA
(Kang et al. 2022)	Crops	Organisational/industry	111	Quantitative	China
(Kathlene et al. 2022)	Humans, crops, livestock	Consumers	830	Quantitative	NZ

Table 6 (continued)

Author & year	Application	Food system actor of interest	Sample size	Study design	Country where data was collected
(Kato-Nitta et al. 2019)	Crops	Consumers & scientists	3197	Quantitative	Japan
(Kato-Nitta et al. 2021)	Tomatoes, pigs	Consumers	4514	Quantitative	Japan
(Kato-Nitta et al. 2022)	Agriculture	Consumers	6939	Quantitative	Japan, USA, Germany
(Kilders & Caputo 2021)	Cows	Consumers	1000	Quantitative	USA
(Kuzma et al. 2016)	Agriculture	NGOs, academia/scientists, government/policymakers & organisational/industry	31	Mixed Methods	USA
(Lassoued et al. 2021a)	Crops	Organisational/industry, government/policymakers & academia/scientists	113	Quantitative	International
(Lassoued et al. 2019a, b)	Crops	Organisational/industry, government/policymakers & academia/scientists	114	Quantitative	International
(Lassoued et al. 2020)	Crops	Organisational/industry, government/policymakers & academia/scientists	99	Quantitative	International
(Lassoued et al. 2019a, b)	Crops	Organisational/industry, government/policymakers & academia/scientists	374	Quantitative	International
(Lassoued et al. 2018)	Crops	Organisational/industry, government/policymakers & academia/scientists	83	Quantitative	International
(Lassoued et al. 2019b)	Crops	Organisational/industry, government/policymakers & academia/scientists	113	Quantitative	International
(Lassoued et al. 2021b)	Crops	Organisational/industry, government/policymakers & academia/scientists	N/A	Quantitative	International
(Lusk et al. 2018)	Food	Consumers	1000	Quantitative	USA
(Maaß et al. 2019)	Wheat	Farmers & organisational/industry	17	Qualitative	Germany
(Mandolesi et al. 2022)	Food	Consumers	102	Mixed Methods	Germany, Italy, Latvia, Netherlands, Spain, Switzerland, UK
(Marangon et al. 2021)	Wheat	Consumers	389	Quantitative	Italy
(Marette et al. 2021)	Apples	Consumers	328	Quantitative	USA, France
(Marette, Beghin, et al. 2021)	Apples	Consumers	328	Quantitative	USA, France
(Martin-Collado et al. 2022)	Meat	Consumers	848	Quantitative	UK
(McFadden and Smyth 2019)	Agriculture	Consumers	Not specified	Quantitative	USA, Canada, Europe
(McFadden et al. 2021a)	Fruit	Consumers	1185	Quantitative	USA
(McFadden et al. 2021b)	Humans, crops, livestock	Consumers	64	Qualitative	USA
(Middelveld and Macnaghten 2021)	Livestock	Industry/organisational & & academia/scientists	26	Qualitative	Netherlands
(Müller et al. 2021)	Livestock	Farmers	20	Qualitative	Germany

Table 6 (continued)

Author & year	Application	Food system actor of interest	Sample size	Study design	Country where data was collected
(Müller et al. 2022)	Livestock	Consumers, farmers, industry/organisational	Not specified	Qualitative	Germany
(Muringai et al. 2020)	Potatoes	Consumers	3161	Quantitative	Canada
(Naab et al. 2021)	Livestock	Consumers	38	Qualitative	UK
(Nair et al. 2022)	Crops	Consumer representatives, government/policymakers, farmers, organisational/industry & academia/scientists	30	Qualitative	Romania, the Netherlands, France, Belgium, Italy, Sweden, UK
(Nawaz and Satterfield 2022a, b)	Food	Consumers	1478	Quantitative	USA, Canada
(Nawaz et al. 2022)	Agriculture	Consumers	19	Mixed Methods	Canada
(Nawaz et al. 2020)	Crops	Organic sector – NGOs, industry/organisational & & academia/scientists	19	Qualitative	Canada
(Nguyen et al. 2022)	Food	Consumers	407	Quantitative	Vietnam
(Nlend Nkott and Temple 2021)	Rice	Industry/organisational actors	38	Mixed Methods	Madagascar
(Ortega et al. 2022)	Rice and pork	Consumers	835	Quantitative	China
(Otsuka 2021)	Food	Consumers	48	Quantitative	Japan
(Pruitt et al. 2021)	Food	Consumers	282	Quantitative	USA
(Robbins et al. 2021)	Agriculture	Consumers	Not specified	Quantitative	USA
(Saleh et al. 2021)	Potatoes	Consumers	643	Quantitative	Switzerland
(Selfa et al. 2021)	Food	Government/policymakers, farm advisors, NGOs, organisational/industry & academia/scientists	45	Qualitative	USA
(Shew et al. 2018)	Rice	Consumers	2315	Quantitative	USA, Canada, Belgium, France, Australia
(Son and Lim 2021)	Soybean Oil	Consumers	200	Quantitative	Korea
(Tabei et al. 2020)	Food	Consumers	28,722	Mixed Methods	Japan
(Tadich and Escobar-Aguirre 2022)	Food	Consumers	702	Quantitative	Chile
(Uddin et al. 2022)	Grapes	Consumers	2,873	Quantitative	USA
(Ufer et al. 2022a)	Pigs	Consumers	203	Quantitative	USA
(Ufer et al. 2022a, b)	Cows	Farmers	361	Quantitative	USA
(van der Berg et al. 2021)	Crops	Organisational/industry, NGOs, & academia/scientists	13	Qualitative	Netherlands
(Vasquez et al. 2022)	Food	Consumers	497	Quantitative	Canada
(Vindigni et al. 2022)	Crops	Consumers	700	Quantitative	Italy
(Wesseler et al. 2019)	Crops	Organisational/industry	75	Quantitative	Netherlands, Belgium
(Yang and Hobbs 2020c)	Crops	Consumers	804	Quantitative	Canada
(Yang and Hobbs 2020b)	Apples	Consumers	697	Quantitative	Canada
(Yang and Hobbs 2020a)	Food	Consumers	697	Quantitative	Canada
(Yunes et al. 2021)	Pigs	Consumers	32,864	Mixed Methods	Brazil
(Yunes et al. 2019)	Cows	Consumers	570	Mixed Methods	Brazil

Table 7 Perceived benefits and concerns of using GETs in agri-food production

Food system actor	Benefits	Concerns	Example articles
Academics/ scientists	Sustainability benefits resulting in public good, i.e., climate change resilience & increased food security **(4)*** Improved food production, i.e., drought tolerance, resistance to pests & diseases, improved food quality, safety, & nutrition **(4)** New job opportunities & economic growth **(4)** Speed, ease, & access to technology **(1)**	Appropriate regulatory restrictions, i.e., regulations that are consistent with risk & international harmonisation Public understanding & acceptability **(9&12)** Technology misuse & unintended consequences, e.g., environmental & ecosystem damage Navigating licensing & patents **(3)** Traceability in the supply chain **(10)** Regulatory restrictions & cost, i.e., reduced regulation needed for easier market entry **(1)**	(Harikrishna et al. 2019; Jordan et al. 2022; Lassoued et al. 2018; Lassoued et al. 2019a, b; Middelveld and Macnaghten 2021; Wesseler et al. 2019)
NGOs	Sustainability benefits resulting in public good, i.e., climate change resilience, increased food security **(4)** Advancing scientific knowledge, i.e., a better understanding of plant biology & breeding	Traceability, i.e., the right to choose non-GE food **(10&11)** Perpetuation of intensive agricultural systems, i.e., monocropping & need for alternative food movements **(6)** Unequal distribution of risks & benefits, i.e., corporate interests prioritised over societal interests **(5)** Power inequality, i.e., fairness to farmers & ownership **(3)** Ethical concerns & naturalness **(8)** Public engagement & governance, i.e., exclusion of the public & non-safety assessments **(12)** Licensing & patents, i.e., a tool to expand corporate power **(2&3)** Impact on local & indigenous communities **(7)** Defining GETs & using appropriate terminology **(9)**	(Bouchaut and Asveld 2020; Helliwell et al. 2019; Jordan et al. 2022; Kuzma et al. 2016; Nawaz et al. 2020; Nlend Nkott and Temple 2021)
Indigenous	Sustainability benefits resulting in public good, i.e., climate change resilience, increased food security **(4)** Enable communities to produce their own food **(4)**	Ethical concerns & naturalness **(8)** Cultural risk, e.g., effect on mauri (life essence) & unintended consequences, i.e., loss of indigenous knowledge **(7)** Unequal distribution of risks & benefits, i.e., corporate interests prioritised over societal interests **(5)** Indigenous seed sovereignty & alternative food movements **(6)** Unknown risks, e.g., environmental & ecosystem damage, biodiversity loss	(Hudson et al. 2019; Kathlene et al. 2022; Nawaz et al. 2020)
Policymakers	Sustainability benefits resulting in public good, i.e., climate change resilience & increased food security **(4)** Improved food production, i.e., drought tolerance, resistance to pests & diseases, improved food quality, safety & nutrition **(4)** New job opportunities & economic growth **(4)**	Public engagement & governance **(12)** Unequal distribution of risks & benefits **(5)** Defining GETs & using appropriate terminology **(9)** Including risk & non-safety assessments in regulations Adaptable regulations to suit evolving technology developments Traceability in the supply chain **(10)** Appropriate labelling standards **(11)**	(Bouchaut and Asveld 2020; Kuzma et al. 2016; Lassoued et al. 2018, 2020; Nlend Nkott and Temple 2021; Selfa et al. 2021)

Table 7 (continued)

Food system actor	Benefits	Concerns	Example articles
Farmers/ farm advisors	Improved food production, i.e., drought tolerance, resistance to pests & diseases, improved food quality, safety & nutrition **(4)** Reduced applications of chemical inputs, water usage & reduced GHG emissions on farm **(4)** Improve animal welfare Enhance economic viability Enable small-holder farmers to produce their food **(4)** Increase biodiversity on farms	Public understanding & acceptability **(9&12)** Seed cost & access, i.e., seeds protected by patents **(2&3)** Economic risk, i.e., uncertain scalability Lack of knowledge **(9)** Unknown risk, e.g., environmental & ecosystem damage Power inequality, i.e., fairness to farmers & ownership **(2)** Inconsistent regulatory standards for export & trade Naturalness **(8)** Contamination of non-GMO farms, co-existence with organic, agroecology, & compatibility with alternative food movements **(6)** Impact on farming communities, e.g., loss of knowledge, decrease in employment **(7)**	(Barrett and Rose 2022; De Jonge et al. 2022; Ferrari 2022; Jordan et al. 2022; Lassoued et al. 2020; Maaß et al. 2019; Müller et al. 2022; Nlend Nkott and Temple 2021; Ufer et al. 2022a, b)
Food industry	Improved food production, i.e., drought tolerance, resistance to pests & diseases, improved food quality, safety, & nutrition Longer shelf-life to reduce food wastage Removal of allergenic compounds, i.e., gluten, lactose	Navigating labelling expectations **(11)** Public understanding & acceptability **(9&12)** Traceability in the supply chain **(10)** Negative publicity & misinformation Inconsistent regulatory standards for export & trade	(Basinskiene and Seinauskiene 2021; Björnberg et al. 2015; Maaß et al. 2019; Nlend Nkott and Temple 2021; Selfa et al. 2021)
Biotech industry	Sustainability benefits resulting in public good, i.e., climate change resilience, increased food security **(4)** Speed, ease, & access (including lower cost) to technology **(1)** Barriers to market entry reduced **(3)** New job opportunities & economic growth **(4)**	Regulatory restrictions & cost, i.e., reduced regulation needed for easier market entry **(1)** Public understanding & acceptability, including negative publicity & misinformation **(9&12)** Inconsistent regulatory standards for export & trade Navigating licensing & patents **(2)** Market power of retailers, i.e., acting as regulators **(3)**	(Bain et al. 2020; Kang et al. 2022; Middelveld and Macnaghten 2021; Selfa et al. 2021; Wesseler et al. 2019)
Consumers	Improved food quality & nutrition, i.e., increased nutrient intake Reduced application of chemical inputs **(4)** Improve animal welfare Sustainability benefits resulting in public good, i.e., climate change resilience, increased food security **(4)** Removal of allergenic compounds, i.e., gluten, lactose	Ethical concerns & naturalness **(8)** Unknown risks, e.g., environmental & ecosystem damage, biodiversity loss Corporate interests prioritised over societal interests **(5)** Trust in institutions, science & technology, & food systems Food safety Industrialised food systems, i.e., monocropping & business models **(6)** Product labelling & transparency regarding technology use **(11)** Technology misuse Expect technology to be regulated in some capacity Lack of knowledge **(9)**	(Cummings and Peters 2022a; Debucquet et al. 2020; Ferrari et al. 2020; Gatica-Arias et al. 2019; Martin-Collado et al. 2022; Müller et al. 2022; Naab et al. 2021; Nawaz et al. 2020; Yang and Hobbs, 2020c; Yunes et al. 2021)

*Similar perceived benefits and concerns were categorised into twelve dominant perceptions (indicated by bracketed numbers 1–12)

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