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Networked framing of GMO risks and discussion fragmentation on Chinese social media: a dynamic perspective

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Genetically modified organisms (GMOs) have been highly controversial in China and beyond. The burgeoning of social media has created an online activist field where participants utilize networked framing practices to engage in connective actions related to GMO risks. However, a dynamic perspective on the co-production of GMO risk discourses has yet to be fully explored, and it is still under debate whether such a collective interpretation is fragmented. To address this gap, this study investigates the risk-invoked GMO controversy by longitudinally exploring the structural characteristics and discursive power structures in the networked framing of GMO risks on social media. This study examines 356,227 GMO risk posts from 2010 to 2020 on the Chinese social media platform *Weibo*. A longitudinal social network analysis and computational text-mining approach are used to construct representation networks among participants based on their joint sponsorship framing practices of GMO risks. The findings suggest that there is a multipolar discussion fragmentation in the networked framing of GMO risks. However, the temporal evidence shows that the risk discussion has become increasingly interconnected and less structurally fragmented over time. In addition, this study highlights the unequal distribution of discursive power among participants; nevertheless, the analysis reveals that this inequality has shown signs of easing over the study period. Overall, this study provides a comprehensive analysis of the GMO controversy from a risk perspective and sheds light on the dynamics of networked framing practices and discursive power structures on social media.

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Introduction

Genetic technologies, particularly genetically modified organisms (GMOs), are essential tools for addressing challenges such as food security, population pressures, and environmental sustainability (Cui and Shoemaker, 2018). Nonetheless, GMOs have been a contentious scientific issue not only in China but also globally for several decades; the debate surrounding GMOs has grown increasingly chaotic in both online and offline public sphere(s) (Jin et al., 2021). While extensive science communication literature has been devoted to unraveling the complexities and chaos behind the diverse public understanding of GMO issues (Jin et al., 2021), current investigations have predominantly focused on the simplistic media representations of multiple discourses and differences among various actors (Yu and Xu, 2016; Zhang et al., 2021) and across media outlets (Ruan et al., 2019). This focus has left a significant gap in examining the risk facet of the GMO controversy.

Risks are at the very core of the GMO controversy and are central to civic initiatives and activism. Sociological studies acknowledge that while controversy and the accompanying activism surrounding GMO encompasses various arguments concerning the technology per se and its socio-economic, legal, and environmental ramifications (Friedrich et al., 2019; Scoones, 2008; Velardi and Selfa, 2021), conflicts over GMO are in essence an epitome of modern risks (Bain and Dandachi, 2014; Motta, 2015) to which the coming together of diverse "cosmopolitan risk communit(ies)" (Zhang, 2018) set out to address. The very logic for this risk-invoked GMO activism is that the enabling and re-embedding effects of risk have fostered a shared understanding, encouraging disparate epistemological communities to coalesce and motivating various actors to take collective actions (Zhang, 2018).

It should be noted that shared risks can also give rise to social divisions due to the "complexity of the concept risk" (Slovic, 1999). In this study, risk is conceptualized as a multidimensional construct (Gui et al., 2018) that goes beyond mere statistical probabilities and consequences traditionally calculated by experts. This broader conceptualization incorporates various parameters into the risk equation, including but not limited to, uncertainty, dread, catastrophic potential, controllability, and equity (Slovic, 1999). This conceptual complexity calls for a comprehensive investigation into how people socially construct and make collective sense of GMO risks, as well as an examination of the extent to which discussions and interpretations of risk are fragmented.

Social media have provided an "online activist field" (O'Neil and Ackland, 2020) where networked yet diasporic participants contest and negotiate the "definition of risks" (Ofori-Parku, 2018) by engaging in the co-production of GMO risk discourses. Nevertheless, a consensus has not yet been reached regarding if and to what extent the collective interpretation of GMOs and the associated risks are fragmented (Debucquet et al., 2020) in the digital media environment. Additional questions arise: Do social media act as public forums (Wang and Song, 2020) for open debate on GMO risks, or do they function more as echo chambers/silos (Schäfer and Metag, 2021) that reinforce pre-existing opinions? Moreover, there has been a lack of scholarly attention to the temporal dynamics of the co-production of GMO risks on social media. Such an omission is problematic, not only due to the ever-changing social media environment, but also because discussions on GMO risks may vary as the issue-attention cycle progresses (Wang and Guo, 2021). Therefore, this study aims to fill these gaps in the literature by adopting a dynamic perspective to deepen our understanding of the emergence, dynamics, and social ramifications of risk-invoked GMO controversy in both the digital and hybrid environment for fragmentation (Pöyhtäri et al., 2021).

China represents a particularly compelling and intriguing case study for this research. Unlike in Western societies where offline protests and campaigns are common and largely permitted, the GMO controversy in China tends to be less contentious and more discursive in form. This debate is primarily mediated and organized through social media platforms. It is against this backdrop that the present undertaking explores digitally mediated GMO controversy in China.

Given the identified gaps in current research and the unique social realties surrounding the GMO controversy in China, this study builds on two strands in the literature: connective movement (Bennett and Segerberg, 2012) and networked framing (Meraz and Papacharissi, 2013). The objective is to investigate how people make sense of multidimensional GMO risks and to explore the potential fragmentation of discussions within the "co-production network of GMO risk discourse" (i.e., *co-production network*) over time in China. To achieve this, the study employs a longitudinal social network analysis, complemented by computational text-mining techniques for topic modeling and frame analysis. The dataset includes 356,227 relevant GMO risk posts from 2010 to 2020 on *Weibo*, China's most popular social media platform. The research not only enriches the specialized field of the social construction of GMO risks, but also extends broader academic discussions on risk communication, digital activism, and social media fragmentation in today's information age.

Empirical background

This section provides a brief background of the ongoing GMO controversy within the Chinese context.

As one of the world's largest emerging economies, China has been proactively pursuing genetic technology as a frontier field since the turn of the century. To this end, the Chinese government initiated a robust biotechnology policy as early as 2000, substantively investing in research and development for GMOs (Jin et al., 2022). Of all the applications, the use of GMOs in agriculture and food production has attracted the most attention and is considered a key component of China's strategy for agricultural modernization (Zhang, 2018). The government was keen to establish a biotechnology-assisted agro-industry to meet multiple objectives: to cater to the needs of its large population, sustain economic growth, and secure national food security (Dirlik, 2002; Lam et al., 2013; Zhang, 2018). The release of the *13th Five-Year Plan for Science and Technology Innovation* in 2016 underscored the government's commitment to promoting the development and commercial application of domestic genetically modified crops (Jin et al., 2022).

Despite this active support, public sentiment toward GMOs has been far less positive and such public opposition has led to a fluctuation in GMO policies. This wavering stems from widespread public concerns about bio-safety and risks, resulting in the suspension of certain development goals in recent years, such as the approval for commercial planting of transgenic crops (Cui and Shoemaker, 2018). Consequently, the Chinese government now confronts difficult decisions about how to balance public skepticism with the potential benefits that the industrialization of GMOs could offer (Jin et al., 2021).

A conspicuous uptick in public opposition has been observed since the start of the decade of the 2010s (Cui and Shoemaker, 2018). Data suggest that the ratio of public support to opposition for GMOs, particularly genetically modified foods, fell below 1 post-2012, plummeting to its lowest point at 0.29 in 2016 (Cui and Shoemaker, 2018). This public skepticism chiefly centers on the unknown risks and potential safety issues (Lam et al., 2013;

Yan, 2012; Zhang, 2018) implicated in GMO applications within the "agro-food system" (Ritzer, 1993).

Notably, the public stance diverges substantially from expert and policy discourses, which argue that GMO risks are "controllable and quantifiable" (Smallman, 2018). Numerous studies have delved into the dynamics of Chinese online discussions surrounding GMOs (Jin et al., 2022; Li et al., 2019) and associated genetic technologies like gene-editing (Chen and Zhang, 2022; Zhang et al., 2021). However, a critical inquiry focusing on the risk aspect of the evolving Chinese GMO controversy is lacking. Moreover, the existing studies suggest that scientific crisis or scandals often act as triggers that shape and diversify public discourse and sentiment. Additionally, certain critical events, such as the "Golden Rice" incident, have significantly elevated public awareness and continuously shape the trajectory of the GMO controversy (e.g., Cui and Shoemaker, 2018; Jin et al., 2022; Li et al., 2019). These observations underscore the necessity for comprehensive investigations into the divergent interpretations of GMO risks across distinct time frames, which are delineated by key events that not only have critical implications for public opinion but may also exert a path-dependency effect on policy decisions related to GMOs and other advanced genetic technologies like gene editing (Kato-Nitta et al., 2021).

Literature review

Navigating the complexities: Battles over the multidimensional GMO risks. The complexity nature of GMO risks offers an initial point for scholarly exploration. Academics have long noted the divide between experts and the public in perceptions of GMO risks (Hartmann et al., 2018; Jin et al., 2021; Kato-Nitta et al., 2021). This division stems from contrasting viewpoints: "risk rationality", which characterized by a scientific yet impersonal approach, and the "rationality of sociality" (Heller, 2001). In this vein, risks act as divisive rather than unifying forces, engendering social divisions as individuals collaboratively construct, yet simultaneously dispute, their own "definition of risks" (Ofori-Parku, 2018). Such an understanding highlights the multidimensionality nature of risk perception (Gui et al., 2018).

Public conceptualization and evaluation of risk go beyond a narrowly-defined, technically-oriented paradigm focused solely on probabilities and consequences (Slovic, 1999). Such perspectives incorporate a wide range of types, scales, and evaluative dimensions of risk, drawing from individuals' lived experiences and localized knowledge (Gui et al., 2018; Ofori-Parku, 2018). In scope, GMO risks span from the personal to the global scale and extend beyond biological risks to include societal risks of various kinds (e.g., Almeida and Massarani, 2018; Gregorowius et al., 2009; Lassen, 2018). Regarding evaluative criteria, while much scholarly work remains focused on physical and tangible hazards, lay perceptions often incorporate factors such as uncertainty, controllability, and specific hazard characteristics (Fung et al., 2018; Lee and Kim, 2018; Slovic, 2001).

Notably, the existing literature lacks a comprehensive understanding of how individuals collectively interpret and navigate the complex and multidimensional GMO risks. This gap warrants closer examination given that the public's co-production of GMO risks exemplifies the process of "riskification" (Hardy and Maguire, 2016). Within this process, various stakeholders strategically frame and problematize GMOs risks, selecting or prioritizing certain risk factors within a broader, multidimensional risk discourse (Almeida and Massarani, 2018; Betten et al. 2018). The driving impetus behind is to control 'problem-setting stories' (Betten et al., 2018) while marginalizing alternative perspectives, thus either reinforcing or resisting/challenging the prevailing risk narratives (Hardy and Maguire, 2016). Importantly, this contestation over the definition of risk serves as an exercise in power, shaping rational approaches to address these pressing risk-related challenges (Ofori-Parku, 2018). As Slovic (1999) put it, "whoever controls the definition of risk controls the rational solution to the problem at hand" (p. 689).

GMO controversy as risk-invoked discursive activism. The intricate landscape of multidimensional GMO risks discussed above necessitates an expansion of analytical scope to consider how these very risks act as catalysts for social movements in general and digitally mediated discursive activism in particular.

As a dominant theoretical underpinning, protests and campaigns against GMOs have been extensively investigated according to social movement theory (Bain and Dandachi, 2014; Motta, 2015; Schurman, 2004; Scoones, 2008). Besides, since the wide application of GMOs in the global agrifood sector, particular attention has been paid to examining *food activism* worldwide (Friedrich et al., 2019; Price, 2021), including diverse forms of campaign activities aimed at criticizing, challenging, and changing the modern food system (Zhang, 2018). These two inherently interwoven strands of literature acknowledge that GMO controversy is rooted in epistemological conflicts among scientific, industrial, and social activist life worlds (Jia, 2022), and that the enabling factor of risks helps to glue various activists into a performative cosmopolitan community and foster the emergence and spread of risk-invoked collective actions (Zhang, 2015, 2018).

Despite the growing body of research on the GMO controversy as a social movement, few empirical studies (Huang, 2018; Jia, 2022) have been conducted in the Chinese context. The GMO controversy as a social movement in authoritarian China has home-grown characteristics. Unlike its Western counterparts, where offline GMO activism of various kinds (Friedrich et al., 2019; Schurman, 2004; Velardi and Selfa, 2021) are to some degree institutionalized, such collective actions in China are by no means institutional and are even unlawful unless approved ex ante (Yang, 2016). Hence, in China, activism regarding the GMO controversy has been linked to a limited "political opportunity structure" (Cammaerts, 2012), thereby rendering it less contentious and more discursive in form. An ethnographic case study (Huang, 2018) has supported this argument by revealing that a group of Chinese left-leaning activists who initiated online protests against GMOs tended to tactically use socialist legacies as discursive repertories to mobilize public attention and bypass censorship.

Notably, digital platforms, be it news portals, blogs, and social media platforms, have improved the discursive opportunity structure (Maier et al., 2018; Motta, 2015) and have been major activist fields in which participants have engaged in "discursive activism" (Shaw, 2016) regarding the GMO controversy in China and beyond. An increasing amount of academic attention has been paid to digitally mediated discursive activism, which has gained significant momentum in the scholarly emphasis on the "political" nature of discursive practice (Clark, 2016). By political, online discourse goes beyond the mere mobilization of cultural resources to trigger sociopolitical change (Clark, 2016) because digital platforms enable activists to negotiate counter-hegemonic discourses and create new claims (Shaw, 2016).

Discursive activism and the logic of connective action. Research on online discursive activism requires a theoretical perspective that could uncover the mechanisms by which isolated and personalized stories and expressions grow into collective actions in a networked environment. Digital media-enabled activism has been extensively analyzed through the lens of connective action

(Bennett and Segerberg, 2012), a framework for understanding large-scale individualized collective actions that are coordinated through and unfold within digital communication networks (Bennett, 2012).

In its broadest sense, connective action can be understood as the logic of "organizing without organizations" (Klandermans et al., 2014), in which digital activism is realized through a self-validating mechanism of information sharing through personal networks online (Wang et al., 2016; Wang and Zhou, 2021). This logic is distinguished from that of collective action in that participants are not necessarily affiliated with the organizers' hierarchical action networks. Instead, they self-organize and coalesce into loosely connected, decentralized, and fluid networks without membership in a social movement or adherence to a collective identity (Khalil and Storie, 2021; Li et al., 2021; Lobera and Portos, 2021; Suk et al., 2021).

Previous studies have focused overwhelmingly on the mechanisms underlying connective action. One strands in this literature has claimed that the affordances (Papacharissi, 2016) and openness (Khalil and Storie, 2021) of digital media have allowed ad hoc issue publics to easily pick up events and engage autonomously in the process of co-production and sharing based on personal expressions. Additionally, empirical research has highlighted the importance of a participatory culture in mobilizing connective action because online interactions create a sense of shared identity and solidarity, enabling virtual communities to rally around particular topics and events (Wang and Zhou, 2021; Xiong et al., 2019). These two lines of thought suggest the significance of network power (O'Neil and Ackland, 2020) in which digital media play the role of organizing agents (Pond and Lewis, 2019).

A major criticism is that connective action prioritizes network structuralism without regard for how participants make sense of social movements (Khalil and Storie, 2021). Two points merit further elaboration. The first relates to the conceptualization and operationalization of interaction networks. Existing literature on connective action tends to center on activists and their information sharing activities by mapping retweeting networks wherein ties represent actual information flows (Wang and Zhou, 2021). The rationale for this kind of operationalization lies in the assumption that retweeting can be deemed as a form of behavioral commitment (Johnson et al., 2020) and as implying public endorsement (Williams et al., 2015). However, this rationale is empirically untenable because retweets do not always necessarily constitute endorsements (Usher et al., 2018). Furthermore, to investigate interaction networks exclusively in terms of sharing/retweeting behavior is to abstract connective structures from the meanings and discourses in which they are clearly situated (Pond and Lewis, 2019), and the neat networking logics and flows of information do not translate into meanings without considering the "ideological component of connective action" (p.16).

Relatedly, the second approach concerns the understanding of meaning making in connective action. Few empirical studies have been conducted to unpack how activists use personal action frames, the transmission units embedded in personalized expressions and discourses (Bennett and Segerberg, 2012), to construct the meaning of connective action by employing frame analysis as an analytical tool (e.g., Li et al., 2021). It is noteworthy, however, that personal action frames result from an interactive process of personalization and sharing (Bennett and Segerberg, 2012) and, consequently, meaning making in connective action resembles an interactional framing process (van Eck et al., 2020) in which activists use strategic framing to construct and adjust their contentious discourses, which further contributes to the co-creation of shared meaning (Wang and Zhou, 2021). In this regard, research on meaning construction in connective action should move beyond simple descriptive analyses of how distinct groups of activists adopt various personal action frames; instead, it is imperative to conceptualize meaning making as co-creational (Xiong et al., 2019) and networked framing (Meraz and Papacharissi, 2013) practices that resort to "alignments negotiated in interactions" (van Eck et al., 2020).

Networked framing and its outcomes. Networked framing refers to a process through which particular problem definitions, causal interpretations, moral evaluations, and/or treatment recommendations attain prominence through crowdsourcing practices (Meraz and Papacharissi, 2013). Compared with the dominant framing paradigm premised on mass media and based on dynamic competition among media elites (Jiang et al., 2016), the underpinnings of networked framing paradigm are giving way to a new era marked by a "hybrid" media environment (Chadwick, 2017), and the focus of which is shifting toward the process of frame negotiation and rearticulation on the front stage (in contrast to the backstage) of negotiation as both elite and nonelite networked agents symbiotically interacting on social media platforms.

Prior research has identified subjective pluralism and diverging interpretive frames in the practices of the networked framing of various issues (Jiang et al., 2016; Meraz and Papacharissi, 2013) by analyzing content and structure formed by the actions of users through addressivity markers. This diversification of public narratives seems to suggest the pluralization of networked framing as a citizens' activity and to reflect the democratic ideals of a networked public sphere. However, this liberal-leaning view has been increasingly challenged. For instance, a recent study by Pöyhtäri et al. (2021), who employed hyperlink analysis to investigate networked framing practices in the refugee crisis debate in Finnish social media and online discussion forum platforms, offered a more pessimistic view. In their study, the results showed the contested use of framing and biased link-sharing behavior among groups of users/sites with differing personal, political, and commercial interests. These observations directly led to the conclusion that the hybrid media environment creates a space for discussion fragmentation (and polarization) in the refugee debate whereby participants are divided into antagonistic camps.

The fragmentation/polarization phenomenon echoes what others in news production process have found in hybrid social media systems. The idea of the "interpretive community" (Zelizer, 1993) is one of the most cited frameworks concerning the mechanism of social interaction and mutual endorsement, through which shared discourse, meanings, and collective interpretations of public events lead to a fragmented understanding of social issues in the digital age (Zhang and Ho, 2022). In addition, homophily mechanisms and/or preferential attachments are scrutinized and confirmed to afford like-minded people the space to collectively crowdsource frames and influential figures and gatekeepers to wield inordinate influence over a crowd (Meraz and Papacharissi, 2013). These studies have shed light on the fact that the collaboration and co-production of online content reflects existing social relations and power structures (Gonzalez-Bailon, 2009; Zhang and Ho, 2022). Therefore, online discourse contributes to the creation, reproduction, and reinforcement of social inequalities of various kinds (Saint-Charles and Mongeau, 2018).

Research questions. To reiterate, the GMO controversy in China resembles a form of risk-invoked connective action that is discursive in form and located within an "online activist field"

(O'Neil and Ackland, 2020) in which networked yet diasporic participants contest the "definition of risks" (Ofori-Parku, 2018) by engaging in the networked framing of GMO risks. However, contrasting viewpoints have been expressed regarding whether social media point to an emerging network sphere (Liang et al., 2019; Wang and Song, 2020) versus a fragmented/polarized media environment (Debucquet et al., 2020; Jin et al., 2022) for the public exchange about and debate on the GMO risks. Considering this and since academic research is still largely understudied whether networked framing contributes to fragmentation, theoretical extensions must consider how co-creational networked framing functions within hybrid media environment for fragmentation/polarization (Pöyhtäri et al., 2021). In capturing and preserving meaning making in the networked framing process of the GMO controversy, this study considers people and content together by constructing *co-production networks*, which I will elaborate on later in this paper.

Additionally, this study tries to tap into the inner logic of *co-production network*. It is expected that crowdsourced and networked framing practices might lead to a fragmentation of the understanding of GMOs risks is due to the productive possibilities of "discursive power" (Jungherr et al., 2019) at the intersection of heterogeneous framing contributors. Since orders of discourse are shaped and constituted by relations of power (Fairclough, 2013), those who possess strong discursive power are more capable of introducing, amplifying, and maintaining frames and even shaping the power balance of information flows (Jungherr et al., 2019), thereby dominating public discourses and controversies regarding the GMO risks that unfold in hybrid media environments for discussion fragmentation.

Because online discussion is a dynamic process, it is highly important to illuminate the evolution of structural features and discursive power distributions with respect to *co-production networks*. Nevertheless, previous longitudinal studies that effectively track changes in the degree of discussion fragmentation across time are relatively rare (Chan and Fu, 2017). In this regard, by targeting an 11-year period (2010–2020) in a longitudinal design, the current study aims to uncover the evolution of the *co-production network*.

Based on the above review, this study addresses the following two research questions (RQs):

RQ1: In China, **(a)** to what extent was the networked framing of the GMO controversy fragmented during the period from 2010 to 2020? **(b)** What is the temporal pattern of the degree of discussion fragmentation as exhibited in time-based *co-production network*?

RQ2: In China, **(a)** how pronounced is the inequality in discursive power among networked contributors engaging in the framing of the GMO controversy during the period from 2010 to 2020? **(b)** What is the temporal pattern of possible unequal distribution with respect to the time-based *co-production network*?

Methods

Data cleaning and preparation. The study builds on data collected from Twitter-like social media platform *Weibo*, one of the largest microblogging platforms in China. By employing a web crawler in Python, 1,295,800 unique posts relevant to GMOs between 1 January 2010 and 30 June 2020 were retrieved using the keyword *zhuanjiyin*. Since this study focuses on the networked framing of GMO risks, a series of data cleaning and preparation work were performed to identify posts and frames that directly concerned GMO risks (see Fig. 1).

Identifying risk posts. To exclude "noisy" posts that were irrelevant to the discussion of GMO risks, a combined top-down and bottom-up filtering strategy was employed. Dictionary-based filtering was first conducted to extract 665,300 candidate posts using a list of predefined risk words that were incorporated into the Chinese version of *Linguistic Inquiry and Word Count, LIWC* (Zhao et al., 2016). Supervised machine learning was then used to classify the candidate posts into established categories, including risk and non-risk posts. Three graduate students were recruited and trained in the human labeling of a 1% ($n = 6653$) random sample of candidate posts. Next, 80% ($n = 5322$) of the labeled posts were randomly selected for training a supervised machine learning classifier, and the remaining 20% were used to evaluate the performance of the algorithm through a five-fold cross validation approach. I then used the well-trained algorithm to perform machine classification on the remaining candidate posts, which yielded a total of 356,227 relevant GMO risk posts for further analysis.

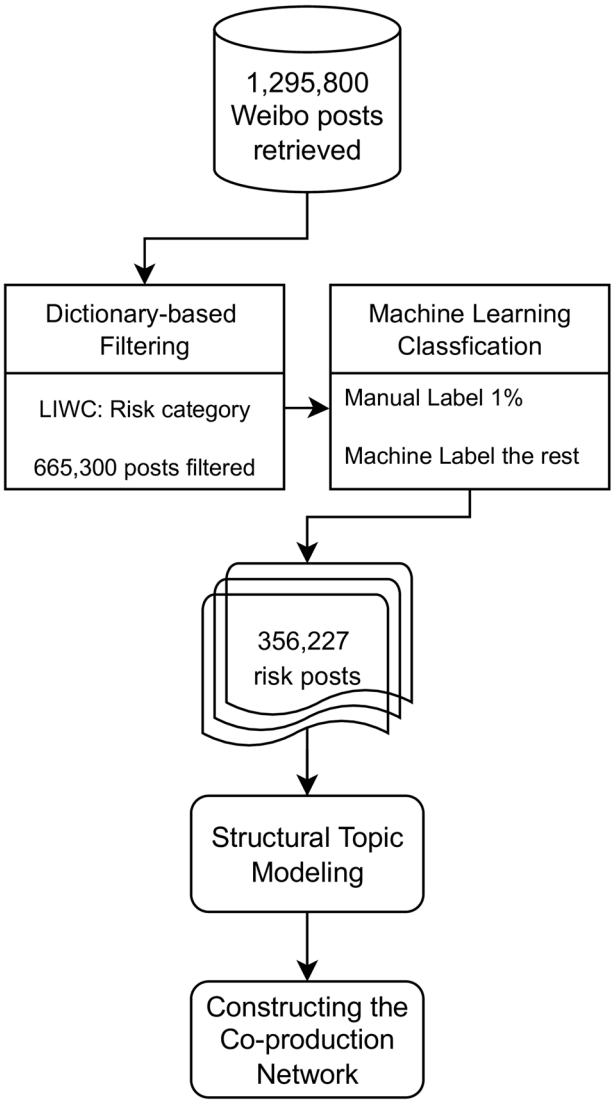

Fig. 1 Sample selection and processing flowchart. Data collection and preparation procedure.

Framing GMO risks. The Structural Topic Model (STM) was utilized to identify frames in the discussion on GMO risks in an indirect manner. I grouped the extracted topics thematically because they did not represent any theoretical concept (i.e., frames in the context of this study) by themselves but required a

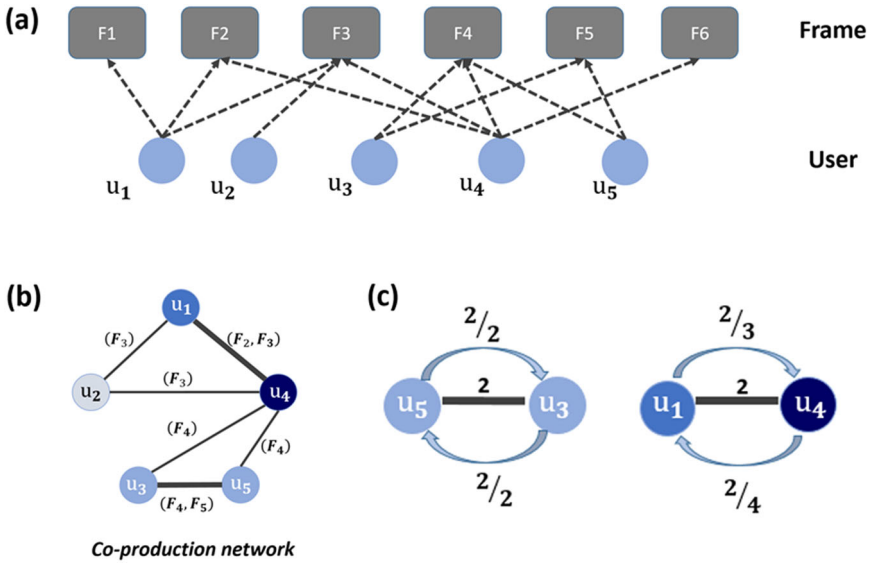

Fig. 2 Logic of the construction and extraction of the co-production network. a Illustration of the affiliation network between the dominant frames and the corresponding users. **b** The co-production network is a weighted and undirected representation network derived from a one-mode projection of the affiliation network at the user level; a tie represents framing coalitions and/or frame co-sponsorship between users, the strength of which depends on the frequency of joint sponsorship for frames along that tie. **c** This subfigure depicts two groups of users and their joint sponsorship practices at the dyad level, exemplifying that the same amount of frame co-sponsorship may carry different meanings. In the left panel, the joint probability of frame co-sponsorship between u_3 and u_5 equals one (2/2 * 2/2), as such, a dyad co-sponsor frames twice, and two share the same number of posts. However, in the dyad shown in the right panel, u_1 and u_4 post three and four messages with respect to GMO risks, respectively, and they do have co-sponsored the frames twice in total; in this scenario, the likelihood of frame co-sponsorship between u_1 and u_4 is 33.33% (2/3 * 2/4), which is far less than that of u_3 and u_5 dyad. This indicates that the actual and meaningful strength of a tie also hinges on the number of frames to which users within a dyad contribute. The colors of nodes in (**b**) and (**c**) indicate the proportion of the number of posts.

secondary labeling procedure and substantive interpretations (Pöyhtäri et al., 2021; Walter and Ophir, 2019). It is noteworthy that all risk posts were pre-processed into a corpus using common methods of text analysis, and the number of topics was determined according to semantic coherence and the exclusivity of the statistical measures. A total of 30 topics were identified and then coded into 13 frames: *problem definition, scientific discovery, naturalness, conspiracy, scientific ethics, (in)justice, general risk, health risk, environmental risk, economic consequence, opposition, industry regulation*, and *event*. The definition of frames and the corresponding topics with keywords have been outlined in Table S1 (see Supplementary Information). Noteworthily, only the dominate frame, which corresponds to the highest topic proportion in a post, was identified and used to construct the *co-production network*.

Co-production network construction and filtering procedures. Much prior research has centered on the issue networks identified through hyperlinks, hashtags, and various addressivity markers such as replies and mentions (Maier et al., 2018; Pöyhtäri et al., 2021; Reber, 2021). Although such manifested ties offer a means to map the structure of actors in topical relationships, they fall short in capturing both the content synchronization and structural connectivity of online public communication. Moreover, the identified topics and frames to which a user contributes are considered external attributes added to nodes, and it is assumed that all pairs of nodes share the same "skeleton" (Reber, 2021) regardless of whether they are actually topically connected in all (sub-)issue spaces. This is problematic since issue networks built on manifested ties could describe the proximity of actors to one another but would be incapable of capturing strategic alliance among users' co-creational and interactional networked framing practices.

To address these limitations and align with emerging trends in social media fragmentation analysis—which increasingly focuses on networks based on users' co-behaviors (Neal, 2014; Saint-Charles and Mongeau, 2018; Mukerjee et al., 2018; Zhang and Ho, 2022)—this study established time-based *co-production networks* over a period of 11 years to longitudinally explore structural characteristics (i.e., *degree of fragmentation*) of the networked framing of GMO risks and the distribution of discursive power. Figure 2 explains the logic of the construction of the *co-production network*. Such a network is a one-mode projection of the affiliation network (Neal, 2014) between the frames embedded in that post and the corresponding contributors/users (see Fig. 2a), wherein the ties represent frame co-sponsorship among networked users (see Fig. 2b). The network construction method used herein shared the similar principle of a representation network in which relationships do not explicitly indicate the flow or exchange of information but are representational in nature. This distinguishes the current study from existing issue network analyses that rely on "physical networks" (Shumate et al., 2013) and focus solely on manifested ties. Instead, this study extends the analysis by centering on hidden ties where interactions are based on users' common niches (Zhang and Ho, 2022). In this case, such commonalities were regarded as the shared congruent framing (Maier et al., 2018) of GMO risks, or at least they were considered to represent strategic framing acts (Guenther et al., 2020) and strategic alliance/advocacy coalitions (Stoltenberg et al., 2019) among the networked participants. It is therefore *co-production networks* publicly render the configurations of users around frames and capture their co-creational and interactional framing practices in the meaning making of GMO risks.

It is noteworthy that the precise specification of networks has become a central issue in the subfield of research on network-based audience fragmentation (Fletcher and Nielsen, 2017;

Table 1 Network-level summaries for time-based co-production networks (2010–2020).

Year	Density	Size	Average LCC	Modularity (Q)	Centralization
2010	0.014	3991	0.245	0.392	0.645
2011	0.009	12275	0.310	0.416	0.733
2012	0.015	24773	0.296	0.332	0.821
2013	0.020	25121	0.242	0.318	0.782
2014	0.022	21303	0.225	0.314	0.855
2015	0.024	16425	0.205	0.311	0.834
2016	0.026	15044	0.201	0.305	0.776
2017	0.024	13378	0.156	0.290	0.836
2018	0.024	18778	0.220	0.313	0.813
2019	0.047	13565	0.180	0.276	0.786
2020	0.025	6206	0.186	0.303	0.654
Mean	0.023	15533	0.224	0.325	0.776

Majó-Vázquez et al., 2017; Majó-Vázquez et al., 2019; Mukerjee et al., 2018). In this regard, a methodological problem concerns the extraction of meaningful ties between networked users. The reason is that a weighted network presents a challenge in "determining how strong an edge's weight must be before deeming it significant" (Neal, 2014). Figure 2c shows the need to filter or extract the backbone of the *co-production network*. Consider, for example, that two dyads of framing contributors have the same amount (twice in this example) of frame co-sponsorship; however, the joint probability of frame co-sponsorship between u_1 and u_4 (33.33%) in the right panel shown in Fig. 2c is far less than that of u_3 and u_5 (100%) dyad because the number of frames to which users within a dyad contributed differed. This asymmetry indicates that the actual and meaningful strength of a tie could not be naively treated as directly proportional to the quality of a relationship but as hinges on the degree to which the observed duplication in frame co-sponsorship exceeds the expected overlap between the two users.

Hence, the present study filtered out weak ties as well as those of random frame co-sponsorship through the calculation of standard *phi* coefficients and *t* statistics for each pair of frame contributors, only the significant ties ($t > 2.58$) were preserved and deemed meaningful. For simplicity, I further excluded noisy nodes (i.e., non-active users who posted only once on *Weibo*) and their connections. These filtering procedures largely reduced the weighted co-production networks to a simple binary one that consist of only meaningful ties. For more additional details, please refer to the Supplementary Information.

Data analysis. Having obtained 11 *co-production networks* identified over a one-year period between 2010 and 2020, this study conducted social network analysis as the level of the whole network as well as for individual nodes for each time-stamped network. As suggested by previous studies (Fletcher and Nielsen, 2017; Maier et al., 2018; Osterbur and Kiel, 2021; Taneja, 2017), summary statistics were calculated address the RQs raised. I utilized network-level metrics, including density, average Local Clustering Coefficient (LCC), and modularity (*Q*), which provide information about the entire network, to examine the degree of structural fragmentation in the networked framing of the GMO controversy and its temporal pattern over the study period (RQ1). Nodes' degree distribution and network centralization, which were based on the node-level degree centrality measure, were employed to investigate the variations in the trend of the possible unequal distribution of discursive power (RQ2).

To facilitate longitudinal analysis, network metrics for each year were aggregated and then mapped on a timeline, adhering to the model of issue-attention cycle (Downs, 1972). As suggested by risk communication studies (Tang et al., 2018), (networked) risk framing may vary as the issue-attention cycle progresses. To this end, the GMO risk discussion is divided into four distinct stages: *pre-problem* (2010–2011), *alarmed discovery* (2012–2013), *realizing the cost of significant progress* (2014–2017), and *post-problem* (2018–2020). The categorization of these four stages is informed by the daily trends in the volume of *Weibo* posts on GMO risks and is corroborated by key GMO events in China, as well as by existing empirical research on issue-attention cycles (e.g., Wang and Guo, 2021) and longitudinal framing analysis (e.g., Domalewska, 2021).

Results

Discussion fragmentation and its temporal patterns. The network-level metrics of time-based *co-production networks* (2010–2020) are provided. The aggregated summary statistics, as shown in the last row in Table 1, indicate the extent of the overall structurally discussion fragmentation (RQ1a). *Co-production networks* are sparse, with an average of 15,533 nodes and a density of 0.023. Density can be interpreted as the level of network integration (Elgin, 2015); in contrast to a dense network which indicates a public sphere for dialog and discussion (Osterbur and Kiel, 2021), lower density in a network represents the evidence of fragmentation (Majó-Vázquez et al., 2017). In this study, the average density manifests that, on average, the possibility of meaningful frame co-sponsorship among users is relatively low (2.3%), signaling that the *co-production network* is fragmented overall. This structural dis-connectivity is further affirmed by the networks' average LCC, that is, an average value of all nodes, which is used to measure the tendency to form communities of nodes or cliquishness in the network (Taneja, 2017). Specifically, the average LCC of the 11 *co-production networks* is 0.224, meaning that an average probability that a randomly chosen user would form a triadic configuration with two of his or her co-sponsors is only 22.4%. This relatively low transitivity implies weak strategic joint sponsorship of the frames and therefore contributes to lower communicative connectivity among the networked users.

Previous studies (Osterbur and Kiel, 2021; Williams et al., 2015) have applied modularity to measure the likelihood of dividing a network into potential communities; a larger modularity value *Q* implies more intracluster connections and fewer inter-cluster relations. In another word, the degree of the structural fragmentation of a network is increased by edges falling within a single cluster, which leads to an increase in *Q*. In this study, the Louvain algorithm is applied to the *co-production network* for each year in the period from 2010 to 2020 to detect communities and generate *Q* scores. The results show that in each year, the network can be meaningfully partitioned into five to seven distinct clusters wherein a group of users have many frame

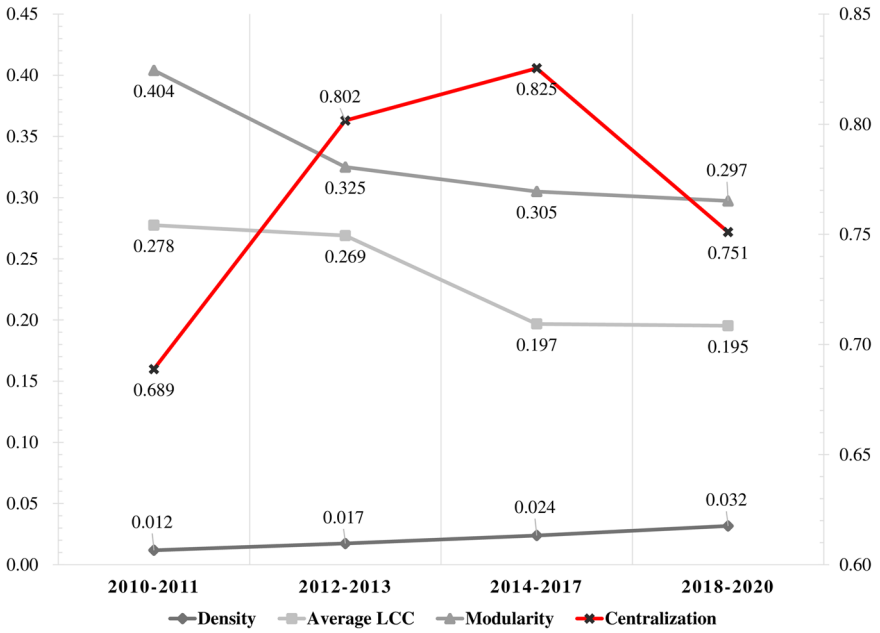

Fig. 3 Temporal trend in the fragmentation of the networked framing of GMO risks. The shift in the network density, average LCC, modularity, and centralization over time.

co-sponsorship ties to each other within a cluster but relatively few shared ties to their out-group counterparts. The average score of network modularity ($Q = 0.325$) is higher than those in previously examined networks (Arlt et al., 2019; Osterbur and Kiel, 2021; Williams et al., 2015), demonstrating fragmentation throughout the networked framing of GMO risks.

Figure 3 clearly visualizes the temporal trend in the fragmentation of the networked framing of GMO risks (RQ1b). At a glance the results in Fig. 3 show that the density, average LCC, and modularity of the *co-production network*, indeed vary over time. The average LCC shows a clear downward trend, indicating a steady decrease from 0.278 from 2010–2011 to 0.195 in the fourth stage (2018–2020). These findings imply that the risk discussion was becoming structurally fragmented. Thus, we expect that its density and modularity would also have shrunk and increased, respectively, during the same period. Paradoxically, however, the results are not in line with these expectations since a steady, albeit slight, increase is observed in the density of the *co-production network*. Furthermore, the trend in modularity Q has been steadily falling during the study period. The scaled modularity score (Shwed and Bearman, 2010) also confirms this trend[1]. The results show that users became increasingly interconnected and bundled into a relatively more cohesive and integrated network over time.

Unequal distribution of discursive power. To address discursive power distribution (RQ2a) and its temporal trends (RQ2b), this study examines the centrality of *co-production networks*; that is, the nodes' degree distribution and network centralization measures. These two metrics are again mapped into four distinct periods for comparison. Overall, the distributions of degree exhibit non-symmetrical and right-skewed during all periods (see Fig. 4). Since the degree measure can be interpreted as activeness or levels of public recognition (Majó-Vázquez et al., 2017), the first message shown in Fig. 4 is that degree is not homogeneously distributed across the nodes of *co-production networks*; instead, only a few high-degree nodes that resemble poles or hubs are directly attach to many low-degree nodes, implying that the discursive power among networked participants is unequal. Such "rich get richer" pattern is robust to an alternative approach to analyzing equality in networked framing[2].

It is noteworthy that in the second message, while node degree distributions are still highly skewed, with a heavy tail on the right side, the right-skewed distributions show decreasing degrees during the period from 2010 to 2020[3]. This downward trend in the skewness of degree distribution implies that the problem of discursive inequities or orders of discourse with respect to the networked framing of GMO risks shows signs of easing over time. This finding is also observed in a reversal of the temporal trend of the standardized score of node degree (i.e., degree centrality)[4]. Based on the node-level measure of degree centrality, the findings show an inverted U-shaped relationship between network centralization and time (see Fig. 3), which I interpret as additional evidence of the increasing decrease in inequality in discursive power after 2014 among the networked frame contributors[5].

Robustness checks

The preliminary results of this study require careful interpretation. Two separate sets of additional checks are performed to ensure the validity and robustness of the findings presented earlier.

Considering the bias induced by the operationalization of networked framing. I employ an alternative approach to assess how the specification of the risk frame and the operationalization of networked framing, represented by the *co-production network*, might influence the results. In this study, only the dominate framing of a post (i.e., the frame with the highest proportion) is utilized for constructing the *co-production network*. This is done regardless of the fact that a complex group of interconnected risk frames, having varying proportions, constitutes the cognitive map embedded within a post.

Cognitive mapping (Tolman, 1932), in this context, refers to the mental process of constructing and organizing the interconnected relationships between various objects or higher-level constructs, such as frames. This network-like structure presents an individual's cognitive understanding of abstract ideas and social realities in the form of a "picture" or "map", thereby

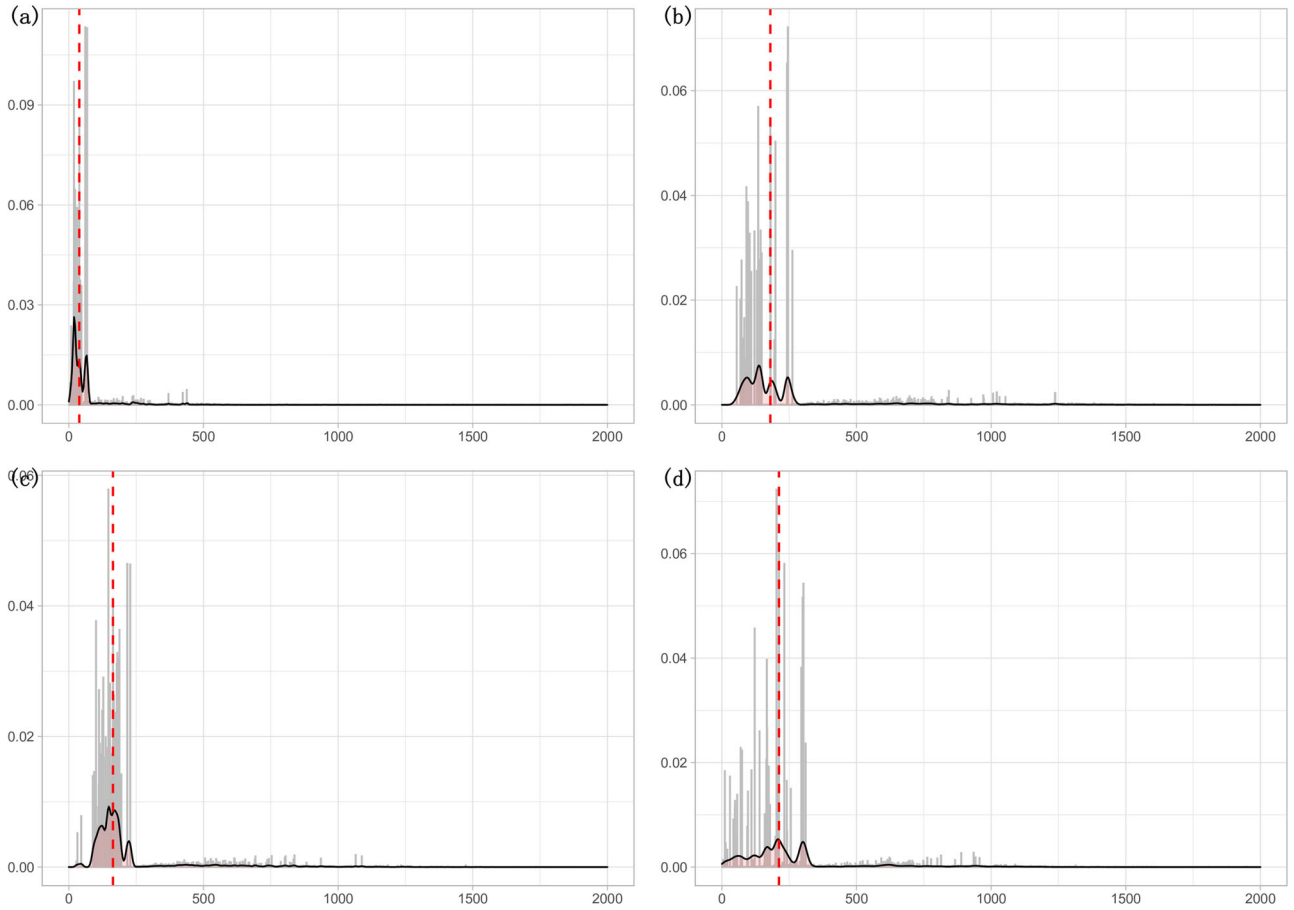

Fig. 4 The shift of the in-degree distribution over time. All subfigures correspond to the four stages identified: (**a**) 2010–2011, (**b**) 2012–2013, (**c**) 2014–2017, and (**d**) 2018–2020. The maximum degree during the four stages are 9106, 20,702, 18,681, and 15,717; only nodes with degree less than 2000 are shown. The vertical line in dash indicates the median number of degree of nodes.

capturing intricate framing and reasoning processes (Guo and Vargo, 2015; McCombs et al., 2014; Tolman, 1932). This structure aligns with the Network Agenda Setting (NAS) theory (Guo and Vargo, 2015; Vargo et al., 2014). According to NAS, the salience of network relationships among networked frames and agendas can be transferred across various sources, such as from news media to the public mind (Guo et al., 2023; McCombs et al., 2014).

In this regard and in accordance with NAS, this analysis takes a more relaxed approach to risk frame specification, preserving all frames within a post, not merely the dominant one. Accordingly, networked framing is operationalized as the correlation or cooccurrence networks between frames in posts within each time period. The stronger the co-occurrence of frames, the higher the correlation between risk frames[6]. Following the guidance of prior research (Fischer-Preßler et al., 2019), 11 time-based temporal frame correlation networks are constructed, in which frames are connected if the pairwise Pearson correlation coefficient between the frame proportion is statistically significant, with adjustments made using the Bonferroni correction for multiple hypothesis tests[7]. Finally, the network summary statistics are aggregated and mapped onto the timeline (see Fig. S1, Supplementary Information).

The results demonstrate a gradual declining trend in the probability of frame cooccurrence over time, as evidenced by a decrease in the modularity score. This indicates a diminishing degree of structural fragmentation within the frame correlation network and suggests that contributors involved in networked framing practices are moving towards framing-consensus formation (Shwed and Bearman, 2010). It is noteworthy that this movement towards a consensus in framing exhibits both a homogenization and a dispersion of risk frames and (niche) narratives across time. Evidence of this trend can also be seen in the slight decrease in network density shown in Fig. S1 and a marked tendency for a rapid growth in the number of isolated nodes within temporal frame correlation networks (see Figs. S2–S12, Supplementary Information) over the study period. Contrary to earlier tendencies that intermingled diverse narrations with differing focuses—a practice that might have muddled and complicated discussions on GMO risks—the emerging consensus in later stages of issue-attention cycle, characterized by reduced cohesiveness in frame cooccurrence, aligns with what Maier et al. (2018) termed "content synchronization." This shift has led to more concentrated and nuanced discursive subspaces, which enables groups of users to discuss GMO risks from similar and aligned perspectives, largely circumventing communication on divergent wavelengths. This ensures that public communication can be more effectively and sufficiently integrated (Maier et al., 2018).

In summary, the results presented above provide strong evidence that the preliminary results are robust to this alternative frame specification and operationalization.

Addressing the bias due to the categorization of risk frames. Considering that a frame is defined as a latent variable that

captures the abstraction notion of groups of thematically similar topics, and that the topical categories extracted from STM are considered "sub-issues" (Maier et al., 2018) embedded within the broader issue of GMO risks, a critical consideration emerges. This consideration pertains specifically to the validity of conclusions and further inferences drawn from the whole *co-production network*. Such validity might be compromised if the findings are not extrapolated to the specific subspaces shaped by these sub-issues. To address this concern, each time-based *co-production network* snapshot is broken down into its constituent sub-issues. This division facilitates the examination of whether the previously established findings are influenced by and sensitive to the categorization of frames.

The summary statistics obtained from the analysis of the extracted 143 time-based sub-issue-dependent *co-production networks*, derived from 13 topical categories across 11 time periods (13*11), yield remarkably consistent results (refer to Table S2 and Figs. S13–S25 in the supplementary information file). The congruence in the findings across the various sub-issue-dependent networks lends further weight to the overall conclusions and suggests that the observed patterns are likely to be substantive rather than artifacts of a specific risk frame categorization or methodological approach. Consequently, these results not only underscore the reliability of the research but also attest to its robustness. Moreover, this additional robustness check enhances the generalizability and applicability of the study, reinforcing its contribution to the field.

Discussion

This study focuses on the controversy surrounding the GMO risks in China. The overarching goal of this study is to investigate online risk-invoked GMO controversy by longitudinally exploring the structural characteristics and changing patterns in the *co-production network* in the context of GMO connective actions embedded in networked and hybrid media environments for fragmentation (RQ1). Moreover, the current study endeavors to gain an in-depth understanding of the process of risk discourse co-production by investigating the productive possibilities of discursive power that could possibly result in temporal changes in the fragmented discussion of GMO risks during networked framing practices (RQ2).

Fragmentation-integration duality in the co-production of GMO risks. A key insight that emerged from the longitudinal network analysis is that the *co-production network* exhibits the co-existence of both fragmentation and integration in the networked framing practices of GMO risks. One the one hand, the evidence presented so far suggests that networked participants cluster around frames of various types. The findings also show that the *co-production network* could be consistently divided into five to seven distinct groups of users based on their joint sponsorship framing practices. These echo chamber-like structures in the co-production of GMO risk discourse manifest discussion fragmentation in a relatively sparse network of ties, as well as a low degree of network cliquishness and weak communicative integration (Maier et al., 2018). In this regard, this multipolar structural fragmentation of divergent interpretive communities challenges binary description of the structure of the GMO controversy in which two competing antagonistic camps of supporters and opponents of GMOs have been extensively observed in both Chinese (Jin et al., 2022) and Western societies (Tosun and Schaub, 2017). This might suggest that conflicting groups are not necessarily structured along binary ideological divisions reflected in dichotomous attitudes toward GMOs; instead, fragmentation could resemble a more complicated pattern of clustering clusters around particular sets of "interpretative packages" (Mann, 2017), and such "non-bipolar clusterization seems to be especially probable for issue or ad hoc publics that emerge on social networks" (Bodrunova et al., 2019) in hybrid social media environment.

One the other hand, the results push forward the existing fragmentation research, which has been conducted mainly on the properties of static network snapshots by examining the temporal evolution of the structural features of *co-production networks*. The findings of this study illuminate the dynamics of risk communities and suggest that fragmentation in *co-production networks* may be less pervasive than previously assumed by scholars of fragmentation. It is noteworthy that whilst distinct clusters of users in a *co-production network* with a reduced but salient community structure are identified, the boundaries between these clusters are trending toward less sharpness, as an increasing proportion of meaningful frame co-sponsorship occurred across rather than within the community boundaries. Perhaps more importantly, this finding indicates that the structure of the debate on GMO risks might show evidence of flattening in the future due to networking logics that discursively bring networked yet diasporic users together and expose them to ideologically disparate/cross-cutting viewpoints (Wang and Song, 2020), despite the fact that they are currently dispersed into balkanized structures. The claim of network integration is partially supported by Jin et al. (2022), who observed that various stakeholders such as governmental actors are increasingly involved in the GMO debate in China. In this sense, the enhanced responsiveness in burgeoning pluralism has encouraged "public trust" and "more knowledge transfer, (which) could be allocated to those target groups" (p.14), thereby narrowing the gaps in the public understanding and interpretation of GMO risks.

To sum up briefly the structure of *co-production networks*, the landscape is far more complex than the simple dichotomy of public forum (Wang and Song, 2020) or public opinion echo chambers and silos (Schäfer and Metag, 2021). The extent of fragmentation in the networked framing practices of GMO risks falls somewhere between these poles. This duality echoes what other scholars have found in other social conflict issues (Bodrunova et al., 2019; Osterbur and Kiel, 2021). This finding is intriguing and of paramount importance because it provides a more nuanced understanding of the relationship between the affordances of social media and the networked public sphere (Pöyhtäri et al., 2021). Although scholars have endeavored to understand whether the transition from low- to high-choice digital environments could generate partition effects and thus lead to increasing fragmentation and polarization, "the empirical evidence does not support more far-reaching claims about a balkanization of the public sphere" (van Aelst et al., 2017). In this respect, I argue that there is a great need for further comparative research on fragmentation in debates on various social issues across time and in different contexts of digital media environments. Contrary to Pöyhtäri et al. (2021), the presents study indicates a much more promising viewpoint of networked framing in a hybrid media environment.

The ebb and flow of discursive power in GMO risk framing. That said, the unequal distribution of discursive power that is dynamic among networked framing contributors is a nontrivial problem that requires further discussion. It is expected that the networked and interactive nature of social media not only will create a space for grassroots organizing and coalition building but also endow heterogeneous users with subjectivity in engaging the meaning making in connective actions through their co-creational framing practices (Bennett and Segerberg, 2012).

Meraz and Papacharissi (2013)'s seminal work has supported this expectation by revealing that the framing power of a crowdsourced group of elites is dependent on the "networked actions of the nonelite as conducted within socio-technical architectures that afford new forms of sociality" (p.23). This reflects a decline in the preexisting gatekeeping power of elite sources, most of which are established news brands, in the pre-Web 2.0 media environment (Jungherr et al., 2019), and an increase in the subjective pluralism of storytelling shaped by a variety of contributors.

Nevertheless, this cannot be essentialized because this form of hybridity not only breeds strong interdependence and horizontal connections with regard to topics and interpretive frames but also reproduces and regenerates what Chadwick (2017) termed power for skilled outlets/individuals in controlling information flows and in exercising discursive power over others (Jungherr et al., 2019). In this regard, the findings of the present study align with this observation by revealing a preferential attachment process (Barabási and Albert, 1999) of the link mechanism in the joint co-sponsorship of GMO risk frames. Such unevenly distributed power with respect to the co-production of risk discourses points to the need to examine the hitherto underexplored process of networked gatekeeping, which is a mechanism parallel to networked framing in that elites are conditioned in symbiotic interrelationships between elites and nonelites and influential sources are crowdsourced to dominate the determination of information relevancy (Meraz and Papacharissi, 2013). In this sense, the current study extends this line of research by providing temporal evidence that the detrimental consequences of emergent elitism, prevalent in networked framing processes within hybrid media environment, appear to be waning. This decline is partially attributable to a slight, yet observable, weakening influence of node degree advantage over time.

Theoretical and practical implications. Broadly speaking, the findings deepen our knowledge of the initiation, evolution, and social repercussions of risk-invoked GMO controversies in both digital and hybrid online environment characterized by fragmentation (Pöyhtäri et al., 2021).

The most significant contribution of this study lies in its provision of a theoretical framework for understanding discussions surrounding risks related to controversial scientific issues, notably GMOs, on social media platforms that fall outside the Western paradigm. While the study is anchored in a Chinese setting, it holds broader global resonance and relevance, particularly as controversies surrounding GMOs and associated risks are gaining increasing significance on the international stage. This study develops and introduces a comprehensive categorization schema comprising 13 GMO risk frames, which captures the multifaceted nature of risk discussions from identification and definition to assessment, attribution, social negotiation, and ultimately to risk distribution, consequences, and management or mitigation strategies (see Table S1 in the Supplementary Information for details). While the frames primarily focus on GMOs, they maintain a level of generalizability to other contentious risk issues, such as worldwide cutting-edge genetic technologies like gene editing (Cui and Shoemaker, 2018; Dahlstrom et al., 2022). This categorization thus offers valuable insights into the nuances of GMO controversy in China and serves as a foundational framework for scholars exploring various ongoing genetic technological risk topics.

More importantly, the increasing global importance of this issue is inextricably linked with the unfolding narratives of other emerging genetic technologies as aforementioned. These technologies are still in their nascent stages and factors such as governance and public polarizing opinions on GMOs indeed create a social context that could have a potential path-dependency influence on the development and acceptance of these emerging technologies (Kato-Nitta et al., 2021). A growing body of literature has started to probe the differences between media portrayals (Dahlstrom et al. 2022) and public interpretations (Nawaz et al., 2022) of GMOs and gene editing. Although there is sporadic evidence that opponents of GMOs have already spoken out against nascent genetic technologies (Cui and Shoemaker, 2018), the aforementioned hypothetical path-dependency effect still requires further rigorous empirical investigations. Thus, the current study may shed light on the potential future of risk communication for GMOs and other more advanced genetic technologies.

From a methodological point of view, the *co-production network* approach diverges from traditional methods by considering the actual content of posts to detect and quantify fragmentation rather than proxies (Bodrunova et al., 2019), thereby extending the research on fragmentation research by providing content-level evidence. Recent studies in social media have increasingly featured networks based on users' co-behaviors (Neal, 2014), such as networks of discourse similarity (Saint-Charles and Mongeau, 2018), audiences overlap (Mukerjee et al., 2018), and co-retweets (Zhang and Ho, 2022). Despite this, such networks are largely overlooked in the domain of social media fragmentation, resulting in a dearth of evidence concerning content-level fragmentation in the academic literature (Huang and Yang, 2022). Additionally, the traditional approach to network construction is highly susceptible to bias. When examining hyperlinked issue networks, for example, researchers employ web crawlers to collect data on link relationships (Maier et al., 2018). These web crawlers necessitate that researchers input seed URLs and set specific parameters like crawling depth and degree of separation. Setting the depth to 1, for instance, restricts the crawler to retrieving only the web pages directly linked to the seed website. Consequently, the choices made for both seed URLs and parameters like degree of separation and crawling depth have a direct influence on the structure of the resulting hyperlink-based issue network (Elgin, 2015), thereby affecting the results. In contrast, the co-production network approach bypasses the need for prior parameter specification and utilizes both hidden and manifested ties, thereby reducing the risk of bias introduced through researchers' choices in sample selection. In summary, further research based on communication networks identified by representational and hidden ties is strongly encouraged to furnish additional empirical evidence on the fragmentation and the distribution of discursive power.

Next to theoretical and methodological implications, this study offers several practical insights that may be of value to scholars and practitioners in the fields of risk assessment, management, and communication. Given the close association between risk and responsibility (Giddens, 1999), it is advisable to integrate the concept and principle of Responsible Innovation (RI) (Malakar and Lacey, 2023; Malakar et al., 2022; Owen et al., 2012; Stilgoe et al., 2013) into the risk governance framework for GMO and more advanced genetic technologies[8]. The AIRR framework—comprising Anticipation, Inclusion, Reflexivity, and Responsiveness—serves as a structured approach to align scientific and technological innovations with democratic principles of transparent, accountability, and meaningful public input (Roberts et al., 2020). Accordingly, I propose specific recommendations based on the four dimensions of the AIRR framework, drawing on study's findings to explore the feasibility of implementing RI practices in genetic technologies.

Firstly, a forward-looking, anticipatory perspective on responsibility in risk analysis and governance (Malakar and Lacey, 2023)

of genetic technologies is crucial. Practical anticipation involves systematically contextualizing the impacts of genetic technologies (Macnaghten, 2016). Such contextualization should be pursued through a comprehensive, multidimensional approach that encourages upstream risk assessment (Kuzma et al., 2008). Unlike traditional technical assessments, which often overlook local knowledge and experiences, a broader risk orientation would enhance the capacity of experts and policy and communication practitioners to manage risks more effectively. The study reveals that public discourse surrounding GMO risks is articulated through various lenses, encompassing diverse scopes, scales, and timeframes. Thus, practitioners should acquire a thorough understanding of public perceptions and opinions on the multidimensional risks associated with GMOs prior to implementing relevant policies or promoting the industrialization and commercialization of GMOs. Importantly, it is incumbent upon practitioners to identify the specific GMO risks currently drawing public attention; equally crucial is the knowledge of how public interpretations might unfold or the anticipation of what would be on the public's radar. By doing so, practitioners can incorporate these insights into technological, policy, and communicative design, thereby facilitating responsible innovation (Nawaz et al., 2022). Strategically, agencies governing GMOs and experts specializing in risk communication can benefit from collaborating with various social media platforms, such as *Weibo*. These collaborations would entail the intentional scraping, analysis, evaluation, and ongoing monitoring of social media data, aiming to understand the evolving public interpretations of the multidimensional GMO risks.

Secondly, relating to the dimensions of inclusion and responsiveness, the recommendation advocates for the inclusion of upstream public engagement and midstream modulation. This approach should encompass diverse perspectives, going beyond those of subject-matter experts (Malakar and Lacey, 2023; Malakar et al., 2022; Roberts et al., 2020). Additionally, the establishment and configuration of new governance architectures (Macnaghten, 2016) should be taken, designed to be responsive to the array of emerging perspectives, views, and norms (Stilgoe et al., 2013). Notably, previous research on RI and deliberation has largely overlooked the heterogeneity of the public and the role social media plays in facilitating bottom-up governance of emerging technologies. It is crucial to acknowledge that the term "public" does not refer to a monolithic group but rather encompasses multiple interpretive communities with varied understandings of GMOs. This heterogeneity manifests as fragmented or "balkanized" structures in networked framing of GMOs risks, as evidence by the time-stamped *co-production networks* analyzed in this study. Consequently, agencies responsible for GMO risk assessment and management must develop finely-tuned strategies targeting these distinct groups. Allocating resources for communication or public outreach must be executed with precision to engage with these specific concerns, serving as a precondition for RI to be truly responsive. Social media platforms are increasingly serving as new governance architecture (Macnaghten, 2016) and pivotal conduits that bridge the gap between diverse public segments and governance institutions. These platforms should evolve to become more interactive, empowering them to strengthen two-way risk communication with the public and foster constructive, ongoing dialogs (Malakar et al., 2022). This will facilitate an engagement that honors a range of viewpoints while maintaining the factual integrity of the discussions at hand.

Lastly, ethical considerations are intimately related to the dimension of reflexivity and must not be overlooked. Specifically, the ways laypersons make sense of GMO risks are deeply anchored in their local experiences and embodied perceptions, a context that cannot be simply overridden by presenting so-called "right" and evidence-based information, which is not without their own biases (Ofori-Parku, 2018). This raises an ethical imperative for a more transparent and introspective nature of reflection (Malakar and Lacey, 2023) in the evaluation and decision-making processes concerning GMO risks. At the institutional level, there is a need for fostering "reflexive scientific cultures" (Macnaghten, 2016) and "reflexive institutions" (Malakar et al., 2022). This will allow all stakeholders, especially the lay public, to question the assumptions and problem framings related to GMOs and associated risks, and ensure that all affected groups have a voice in determining risks and solutions (Nawaz et al., 2022).

Limitations. This study comes with its own set of biases and limitations. First, the "sample selection bias" could confound the results due to two primary factors. The first factor is the non-transparent or "black-box" nature of data retrieval from social media platforms, specifically *Weibo* in this case, which compromises the study's methodological rigor and overall validity. The second factor concerns the self-selective nature of social media engagement. Given that not all individuals are equally active in online discussions about GMOs, the sample is biased towards users who have expressed a high level of concern and have explicitly articulated their viewpoints on GMO risks, leading to a somewhat imbalanced representation of individuals participating in networked framing practices. For future research concerning the GMO controversy in China, it would be advantageous to collaborate with *Weibo* to obtain a more extensive and balanced sample and to test the robustness of the findings. Second, while this study zooms in on *Weibo* as a focal platform, extending research to other platforms such as the question-and-answer platform *Zhihu* could offer a more nuanced, comparative perspective (Yang, 2022). Lastly, the findings of this study are not generalizable outside of China without further comparative analysis. Investigations into how networked framing of GMO risks varies across different national contexts are desperately needed. This would enable more cross-cultural observations, and could involve comparing the GMO controversy in China with discussions on Western platforms like Twitter.

Data availability

The datasets generated or analyzed during the current study are not publicly available as they form part of the author's ongoing research. They are available from the corresponding author on reasonable request.

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Notes

1 Shwed and Bearman (2010) differentiate two forms of contestation that co-exist temporally: epistemic rivalries and benign contestation. Compared with epistemic rivalry that are the substance of severe contestation in which strongly entrenched camps disagree on core issues, the benign one can be conceived as the normative level of contestation or fragmentation, which is result from actors' efforts to establish their own niches and subdivisions in the course of specialization and professionalization in certain fields and is a factor of size of network that epistemic community members endeavor to create. In their study, the authors use the scaled raw modularity score (i.e., raw modularity divided by logged network size) to accurately detect the level of epistemic rivalry (Shwed and Bearman, 2010). Such a measure helps to rule out the component of benign contestation that could confound and conflate modularity since benign contestation usually creates salient network communities as well as drives the raw modularity score up. In this study, the steadily decreasing trend in scaled

modularity is also evidenced during the study period. The mean scores of the scaled modularity in the four stages are as follows: 0.252 (2010–2011), 0.310 (2012–2013), 0.254 (2014–2017), and 0.222 (2018–2020).

2 I fit the power law distribution of degree, the result shows that the node degree follows power law-like distributions over time ($Mean_{\alpha} = 2.03$, mean of the Kolmogorov–Smirnov statistic $D = 0.03$), with only a very weak fluctuation in the value of the exponent α ($SD = 0.02$). Moreover, all annual assortativity coefficients, which measure the level of homophily of the network based on the node degree, are negative ($Mean = -0.21$, $SD = 0.05$), suggesting that the co-production networks are heterogeneous. These results indicate the robustness of the findings.

3 The Fisher-Pearson coefficients of skewness are calculated for the distributions of node degree.

4 The mean values of the degree centrality in the four stages are as follows: 0.011 ($SD = 0.037$), 0.017 ($SD = 0.050$), 0.024 ($SD = 0.061$), and 0.032 ($SD = 0.071$). The results show that all increases in degree centrality are statistically significant ($p < 0.001$).

5 While density describes the general level of cohesion, centralization describes the extent to which this cohesion is organized around particular focal points by measuring the degree to which a network is dominated by a single node or a small group of nodes. The network with a centralization score of 0 represents a decentralized network, and a value of 1 represents a highly centralized one.

6 Only positive correlations show between frames above a predefined threshed, indicating that both frames are likely to be used within a post and therefore are considered linked to each other.

7 Correlation matrix for constructing the frame cooccurrence networks are available upon request.

8 As a conceptual model of responsibility, RI has gained significant traction in academic, policy, and professional spheres in recent years (Stilgoe et al., 2013). RI integrates broader societal and ethical considerations into the processes of science and innovation (Stilgoe et al., 2013) that make it a priority in risk governance and decision-making. Unlike traditional retrospective approaches to risk analysis and governance, RI adopts a forward-looking perspective, taking care of the future through collective stewardship of science and innovation in the present (Stilgoe et al., 2013). While RI has been extensively applied to emerging and disruptive technologies like nanotechnology (Malakar and Lacey, 2023; Malakar et al., 2022), its incorporation into discussions surrounding mature genetic technologies—which have already elicited significant social and political controversy—remains limited (Macnaghten, 2016; Roberts et al., 2020). There are a few exceptions that have explored the potential for and challenges of implementing RI in the field of genetic technologies. These studies primarily focus on Global North economies such as Europe (Macnaghten et al., 2021) and the United States (Roberts et al., 2020), with some examination of Global South contexts like Brazil, India, and Mexico (Macnaghten, 2016).

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