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Chinese public perceptions of food applications based on synthetic biology

ABSTRACT

Synthetic biology (SB) is an emerging area of technological innovation with potential to be applied across a range of sectors, including within agri-food production. However, societal responses to SB and its applications will shape its development, commercialization and regulation trajectories. This research aimed to understand Chinese public responses to SB food in general and in relation to specific agri-food applications using an online survey (n = 1,330) and structural equation modelling. The results showed Chinese respondents have slightly positive attitudes towards SB food in general. Respondents reported an overall acceptance of SB soybean and SB yeast but rejected an SB pig. Of the included factors, benefit perceptions were the most influential in shaping acceptability. Affective reactions influenced benefits perceptions more than risk perceptions across all the applications. General attitudes towards SB food can positively affect the acceptability of specific applications directly, and indirectly *via* benefit perceptions. Greater perceived unnaturalness was a strong predictor of respondents' risk perceptions but not of application acceptability. These results suggest that regulations for SB agri-food applications might most align with societal priorities if developed on a case-by-case basis. Furthermore, regulatory frameworks and emerging commercialization strategies should consider the roles of multiple factors to address specific public perceptions and attitudes.

Keywords: synthetic biology, food innovation adoption, risk-benefit-acceptance model, dual-process theory, affective reaction, perceived unnaturalness

1. Introduction

Synthetic biology (SB) is a multidisciplinary research area that applies engineering principles to create new biomolecular components, networks and pathways, and uses these "bio-bricks" to "reprogram" organisms (Khalil & Collins, 2010). Through engineering and redesigning the entire processes of organisms, SB tools have enabled a variety of applications to overcome the challenges that cannot be easily solved using existing biological approaches. These novel SB applications can offer new and cost-effective ways of disease treatment, enzyme, drug and clean energy production, waste recycling, agri-food production, species management (saving species from extinction or eliminating specific species) and environmental enhancement, *inter alia* (Batista-Silva et al., 2020; James et al., 2018; Polizzi et al., 2018). Within the agri-food sector, at present, there are some SB-based innovations that intend to facilitate the development of new crop variants; the production of novel food, food ingredients and food packaging; the process of food and food waste; and the improvement of the breeding and management of livestock (e.g. improving livestock traits to reduce the use of veterinary drugs) (Lv et al., 2021). For example, Modrzejewski et al. (2019) identified 99 market-driven applications of SB across 28 different plant species targeting distinct traits (e.g. increased agronomic value, improved food and feed quality, increased biotic stress tolerance, and generation of herbicide tolerance).

Scientific development associated with emerging technologies must be transparent, with the application of rigorous ethical and legal standards and proceed at a high level of social acceptance (Stilgoe et al., 2013). Failure to address public preferences and concerns at an early stage in the innovation process might lead to societal rejection of the technology and/or its applications, and to the *post hoc* production of complex and potentially unstable regulations and policies (Mehta, 2004). SB has potential to radically alter the genetic makeup of not only domesticated organisms but also wild populations, posing benefits and risks to human and environmental health as well as ethical concerns, which implies that societal engagement is an important priority (König et al., 2010). As part of this, it is necessary to consider how SB applications are *perceived* by different stakeholders, including the general public, to align product development and regulation with social priorities and preferences. In particular, the agri-food sector represents an important segment of the global SB market, but at the same time has been projected to be the focus of more negative public responses compared to the healthcare, energy and environmental sectors (Betten et al., 2018).

This research is focused on China, a major player in the world's synthetic biology market. According to BCC Research (2022), the global market for SB reached $9.5 billion in 2021 and is forecast to grow to $33.2 billion by 2026. In China, a massive expansion of research investment and policy support has recently been undertaken to facilitate SB development, including that within the agri-food sector. It has also seen a dramatic increase of the number of SB publications by China-based authors, which accounted for 7% of the world's SB publications (Shapira et al., 2017). Chinese scientists perceived the public to be unfamiliar with SB (reasoning that SB was a very new area of research) and potentially transfer their attitudes towards genetically modified food to SB food-related applications, leading to social resistance and rejection of different SB food applications (Jin et al., 2021). Despite so, no systematic approaches have been established to address relevant social implications due to the lack of relevant social science research (Li & Shapira, 2015; Shapira, Kwon, & Youtie, 2017; Zhou, 2015).

Researchers have called for further research into public perceptions and attitudes associated with SB and its specific applications, which at time of writing has been underexplored (Jin et al., 2019; Ribeiro & Shapira, 2019; Trump et al., 2019). It is particularly important to consider different types of SB agri-food applications when evaluating public responses as it can inform future product development and commercialization, as well as policy making. More targeted and effective strategies may be achieved by developing and testing a model that indicates how the included factors interact and shape SB food acceptance (Jin et al., 2019). Three SB agri-food applications at an early stage of the innovation process were thus identified in this research, in order to forecast Chinese public perceptions and acceptance. This research aimed to answer the following questions:

- What are Chinese public attitudes towards applying SB to the agri-food sector in general?
- Are there attitudinal differences regarding different SB food applications?
- What drives public acceptance of agri-food applications of SB in China?

2. Literature Review and Model Development

2.1 Theoretical foundation

The proposed model is an extension of the "risk-benefit-acceptance" model, which has been applied to explain people's acceptance of emerging food technologies and/or their applications based on their risk and benefit perceptions (Frewer et al., 2011), e.g. in relation to genetic modification (GM) technology (Jin et al., 2022), nanotechnology (Gupta et al., 2015), food irradiation (Behrens et al., 2009), high pressure processing (Olsen et al., 2010), and pulsed electric field processing (Nielsen et al., 2009). The "risk-benefit-acceptance" model, however, failed to indicate how people make a judgement regarding which benefits and/or risks are relevant. Three other factors (general attitudes towards SB applied to the agri-food sector, affective reactions to and perceived unnaturalness of SB applications) were thus added to the "risk-benefit-acceptance" model to not only predict people's acceptance of, but also explain their risk and benefits perceptions of SB applications.

Affective reactions were considered in terms of their influence on judgements of risks and benefits associated with, and final acceptance of, SB applications. The rationale for this was grounded in dual-process theory, which emphasizes the parallel operation and interaction of two modes of thinking (analytic thinking and experiential thinking) in human decision-making. Specifically, in responding to uncertain and complex situations, experiential thinking, which is more intuitive and affect-based, may be more efficient in reaching decisions than analytic thinking, which applies in-depth and logic analysis of the available evidence to make decisions (Epstein, 1994). E.g., Finucane, et al. (2000) reported that people are prone to using their affective reactions to a stimulus item (i.e. positive or negative feelings about specific objects, ideas or images) to improve risk and benefit judgmental efficiency. Given that SB applied to the agri-food sector may involve risks which are perceived to be uncertain and difficult to quantify, affective reactions to different SB applications were assessed in terms of their role in relation to experiential thinking and public acceptance of SB applications.

2.2 Hypotheses and Model Development

2.2.1 Risk and benefit perceptions

There is evidence that both benefit and risk perceptions inform public acceptance of applications of novel food technologies, in which benefit perceptions generally deliver positive impacts while risk perceptions deliver negative impacts (Fischer & Frewer, 2009; Siegrist et al., 2007). Similar effects of benefit and risk perceptions were also found in some studies into public responses to SB as an enabling technology (Akin et al., 2017; Ineichen et al., 2017; Pauwels, 2013). Thus, we assumed in terms of specific SB agri-food applications, similar effects of benefit and risk perceptions on acceptability could be identified among the Chinese public, thereby leading to the following hypotheses:

Hypothesis 1a: *The perceived risk associated with an SB food application has a negative effect on the acceptability of that application.*

Hypothesis 1b: *The perceived benefit associated with an SB food application has a positive effect on the acceptability of that application.*

2.2.2 Perceived food unnaturalness

SB involves deliberate changes to organisms at the genetic level. Its applications may be perceived as challenging the natural order, as was the case for GM technology (Knight, 2009). This can lead to public moral and ethical concerns about SB food applications, sometimes expressed as "playing God", "interfering", or "tampering with nature and natural processes" (Pauwels et al., 2012; Rogers, 2011). Thus, using SB to produce and process food may be perceived as being unnatural (Román et al., 2017; Rozin et al., 2009). Dragojlovic and Einsiedel (2013) reported food based on SB yeast was perceived to be unnatural, which correlated with higher risk perceptions and lower benefit perceptions and acceptance. Similar findings have also been found in research on Chinese public responses to GM foods, where perceived unnaturalness has been reported to correlate with higher perceived risk and lower perceived benefit and acceptability. Therefore, we hypothesized that the perceived unnaturalness of food based on SB applications negatively affects Chinese public perceptions of benefits, application acceptance and increases their risk perceptions.

Hypothesis 2a: *Greater perceived unnaturalness of food produced using SB increases the perceived risk of that application.*

Hypothesis 2b: *Greater perceived unnaturalness of food produced using SB reduces the perceived benefit of that application.*

Hypothesis 2c: *Greater perceived unnaturalness of food produced using SB reduces the acceptability of that application.*

2.2.3 Affective reactions

Rapid emotional or affective responses have been reported to impact on people's evaluative judgements (Epstein, 1994; Slovic et al., 2004). For example, the positive affective responses to nanofoods have been reported to reduce consumers' risk perceptions, and increase benefit perceptions and acceptance (Siegrist et al., 2007). Negative affective reactions (e.g. disgust evoked by cultured meat) were found to reduce Chinese people's acceptance (Siegrist & Hartmann, 2020b). Therefore, the following hypotheses were developed to assess the influence of Chinese public affective reactions to specific SB food applications on their perceived risks and benefits as well as their acceptance of these applications.

Hypothesis 3a: *Positive affect evoked by an SB food application reduces the perceived risk of that application.*

Hypothesis 3b: *Positive affect evoked by an SB food application increases the acceptability of that application.*

Hypothesis 3c: *Positive affect evoked by an SB food application increases the perceived benefit of that application.*

Previous research has indicated a negative correlation between people's affective reactions and perceived unnaturalness associated with emerging food technologies, but the direction of this relationship has been inconclusive. Some researchers assumed that perceived unnaturalness associated with emerging food technologies (e.g. cultured meat and GM food) has a negative impact on affective reactions (Siegrist et al., 2016; Siegrist & Hartmann, 2020b). The other researchers, however, assumed the reverse direction, claiming that perceived unnaturalness may be a *post hoc* rationalization of, or explanation for, people's negative affective reactions (Greene & Haidt, 2002; Haidt, 2001; Wilks et al., 2021). Since there is evidence that few Chinese survey participants associate GM food applications with perceived unnaturalness immediately after reading the information about those applications (Jin et al., 2022), it has been assumed in the present research that Chinese people's affective reactions to an SB food application are more likely to precede and result in a negative impact on their perceived unnaturalness of food produced using this application.

Hypothesis 3d: *Negative affect evoked by an SB food application increases the perceived unnaturalness of food produced using this application.*

2.2.4 General attitudes towards GM and SB food

An attitude is defined as "*a psychological tendency that is expressed by evaluating a particular entity with some degree of favour or disfavour*" (Eagly & Chaiken, 1993). General attitudes towards a food technology represent an individual's overall tendency to approve or disapprove of that food technology application (e.g. GM and SB), which can subsequently affect their interpretation of the available information about the technology and specific applications. E.g., there is research showing negative general attitudes towards GM food may bias people's evaluation of specific GM food applications, resulting in more negative affect, lower perceived benefit and acceptance, and higher perceived risk (Bredahl, 2001; Jin et al., 2022). Bredahl (2001) reported that Italian consumers' general attitudes towards GM food have a strong positive impact on the perceived naturalness of the yoghurt produced using GM yeast. A similar relationship was observed for Chinese consumers in relation to GM yeast for producing vitamins (Jin et al., 2022). Thus, attitudes towards SB food in general were assumed to affect people's affective reactions, evaluation of risks, benefits and food unnaturalness as well as acceptability associated with specific SB food applications (Hypothese 4a-e). These hypotheses also imply that the relationship between people's attitudes towards SB food in general and their acceptance of specific SB food applications can be mediated by affective reactions, evaluation of risks, benefits and food unnaturalness associated with these applications.

Hypothesis 4a: *A positive general attitude towards SB food has a positive effect on their affective reactions to an SB food application.*

Hypothesis 4b: *A positive general attitude towards SB food reduces the perceived unnaturalness of an SB food application.*

Hypothesis 4c: *A positive general attitude towards SB food reduces the perceived risk of an SB food application.*

Hypothesis 4d: *A positive general attitude towards SB food increases the perceived benefit of an SB food application.*

Hypothesis 4e: *A positive general attitude towards SB food increases the acceptability of an SB food application.*

However, at present, the public are still relatively unfamiliar with SB as an emerging area of research and application. There is evidence that Austrian citizens may use GM as a "comparator" technology to "make sense" of SB applied to food production, i.e. an individual's prior attitudes towards GM food could potentially inform their general attitudes towards SB food (Steurer, 2015). People's general attitudes (e.g. towards science, biotechnology and the environment) may also affect their attitudes towards specific technologies, such as GM (Bredahl, 2001; Chen & Li, 2007), gene editing (GE)[1] (Chen & Zhang, 2022), and SB (Akin et al., 2017; Kronberger et al., 2012). This can explain the significant positive correlation which has been observed between people's attitudes towards GM and GE (Nguyen et al., 2022). General attitudes can be confounders that have caused a

[1] GE manipulates the genome of the original organism by removing or replacing a targeted gene, and can be fast, accurate, and without the introduction of foreign DNA fragments.

significant correlation between people's prior attitudes towards GM and their attitudes towards other biotechnologies.

In GM technology foreign DNA is inserted into host organisms to produce desired traits (Colwell et al., 1985). SB technology can more radically alter the genetic makeup of species or even create organisms using basic molecular components, which might evoke more prominent ethical concerns within society (Bedau et al., 2009; Steurer, 2015). Despite the technical differences, GM and SB both involve deliberate change to organisms at the genetic level. For this reason, some people may use GM as an anchor to "make sense" of SB (Steurer, 2015),resulting in existing general attitudes towards GM influencing thei general attitudes to SB. Others may clearly distinguish SB from GM, but a significant correlation may still exist between people's existing, or "prior" attitudes and their general attitudes towards SB, as both are influenced by general attitudes towards science or biotechnology (Akin et al., 2017; Kronberger et al., 2012). Therefore, rather than assuming an effect of prior GM attitudes on general attitudes towards SB, it was assumed:

Hypothesis 5: *People's prior attitudes towards GM food are a significant predictor of their general attitudes towards SB food.*

In accordance with the existing literature on public responses to emerging food technologies, a total of 17 hypotheses were developed, of which hypotheses 1-4 informed the development of a model explaining attitude formation towards SB agri-food applications (Figure 1).

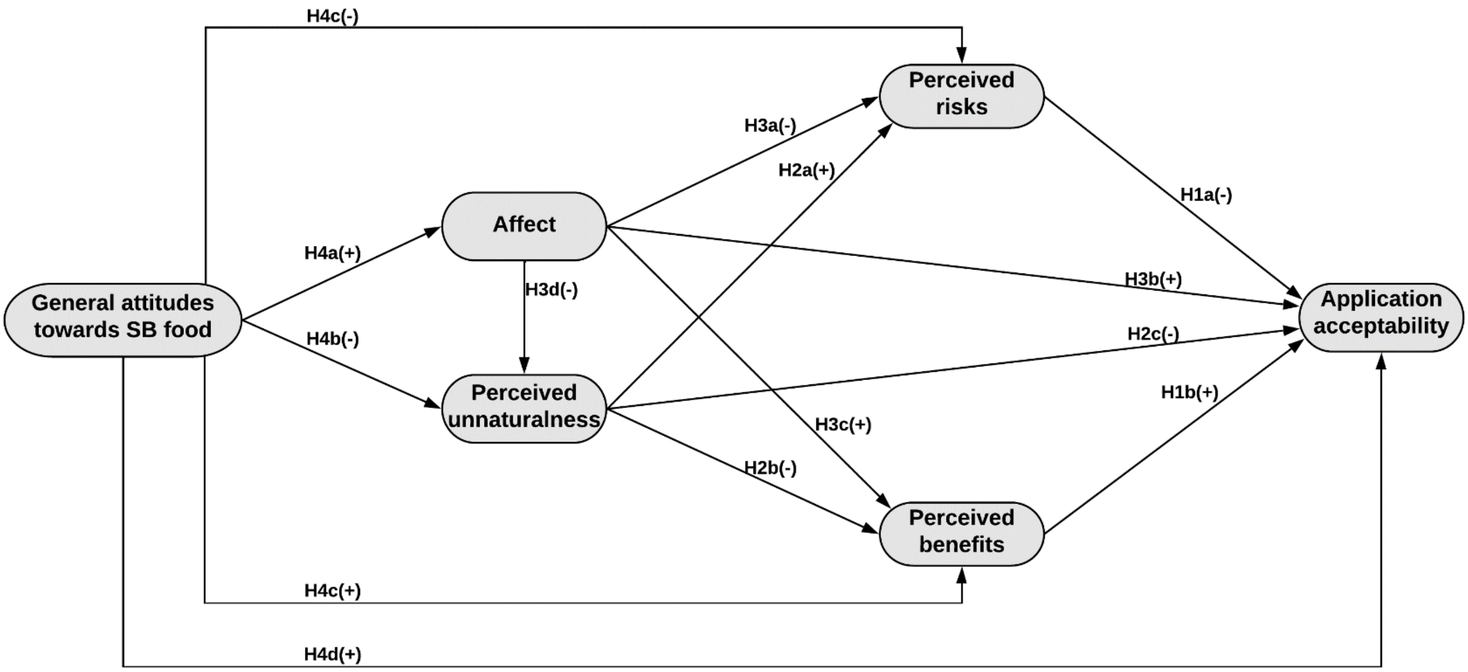

Figure 1. Model of attitude formation towards SB agri-food applications

Note: The direction of the hypothetical relationship is specified in parentheses.

3. METHODS

3.1 Questionnaire design

A questionnaire was developed to gather the required data. The design of the questionnaire was informed by the existing research into attitudes towards GM food (Costa-Font & Gil, 2009; Dunlap et al., 2000; Frewer et al., 2003; Poortinga & Pidgeon, 2005; Schnettler et al., 2017; Siegrist, 2000), and was informed by focus group discussions conducted in Nanjing and Shenzhen (three groups for each city; n = 32 in total for all focus groups, in which few participants had heard about SB before). These focus groups were conducted to elicit Chinese people’s habitual expressions regarding their perceived risks, benefits and ethical issues associated with SB applications. The questionnaire was designed to obtain data on the following constructs: prior attitudes towards GM food; general attitudes towards SB food; affect, risk perceptions, perceived unnaturalness, benefit perceptions and acceptance associated with the selected SB applications (Supplementary Material Section One, Table A). One confounding factor regarding the relationship between prior attitudes towards GM food and general attitudes towards SB food is that this relationship is potentially driven by individuals' general attitudes towards novel food technologies and/or their environmental worldviews (Hall & Moran, 2006; Vidigal et al., 2015). To address this, items testing food technology neophobia[2] (Cox & Evans, 2008) and "balance of nature" and "human domination" environmental worldviews[3] were included in the questionnaire to be used as control variables for the relationship (Kellert, 1996).

All the constructs in the questionnaire were measured by asking respondents to indicate the extent of their agreement or disagreement with different statements on five-point Likert scales (anchored by 1 = "strongly disagree" to 5 = "strongly agree") with the exception of the assessment of affect. To elicit respondents' affective reactions to these applications, respondents received introductory information about each application (Supplementary Material Section One, Table A), and were asked "*What is the first thought or image that comes to your mind after you read information about this application?*". Subsequently, participants were asked to rate their levels of positive or negative affect associated with this first thought or image, based on seven-point scales (1 = "extremely negative" to 7 = "extremely positive"). The technique has been used to elicit people's affective reactions to climate change, nanofoods and GM foods in previous research (Jin et al., 2022; Leiserowitz,

[2] Food technology neophobia refers to people's fears of novel food technologies.
[3] A dominionistic worldview refers to beliefs that humans have mastery or control over nature. A moralistic worldview refers to the belief in the spiritual reverence of nature.

2006; Siegrist et al., 2007). Demographic information was also collected including gender, location, occupation, educational level and personal monthly income.

3.2 Sampling and Distribution

Ethics approval for the present research was granted by the lead researcher's university in July 2019 (Ref: 13967/2018). A pilot study was conducted using 130 respondents in China and a revised questionnaire was developed. The questionnaire was then distributed online in two Tier 1 (Shenzhen and Beijing) and two Tier 2 (Nanjing and Wuhan) Chinese cities by a social research company (Beijing Jishuyun Technology Co., Ltd)[4]. The company sent invitations via WeChat to their panel which consisted of 1,075,809 members covering different socio-demographic groups[5]. Before participating in the survey, the members were informed of the voluntary participation; the anonymity and confidentiality the survey; their right to quit at any time when answering survey questions as well as to withdraw their own response after completing the survey. There were 1,500 members who agreed to complete the survey, and 1,330 compete responses were finally obtained in October 2020 for data analysis. The participants were provided with a small incentive payment (10 Chinese yuan). The mean age of respondents was 35 (SD = 11), compared to a national mean age of 38, and 48% of the respondents were female compared to 49% of the national population (National Bureau of Statistics of China, 2021). The socio-demographic attributes of survey respondents are shown in Table 1. All the collected data have been stored in the secure online cloud (Microsoft OneDrive) provided by the lead author's university during the project's lifetime. At project end, the data will be uploaded to the university's research data repository and stored for at least 10 years. Those stored in Microsoft OneDrive will be deleted.

[4] Shenzhen and Beijing are Tier 1 cities, representing the most economically developed regions in China. Nanjing and Wuhan are capital cities at the provincial level and are Tier 2 cities that are fast developing.
[5] The socio-demographic attributes include gender, age groups, educational levels, geographic locations, personal and household income levels, marital status, family structure and profession.

Table 1. Sample characteristics

Characteristics		Number	Frequency
Gender	Male	692	52%
	Female	638	48%
Age	18-24	267	20%
	25-34	412	31%
	35-44	319	24%
	45-54	260	20%
	>54	72	5%
City	Shenzhen	401	30%
	Beijing	303	23%
	Nanjing	359	27%
	Wuhan	267	20%
Occupation	Company employee	889	67%
	Government employee	77	6%
	Self-employed	182	14%
	Student	82	6%
	Others	100	7%
Highest Level of Educational Attainment	Secondary school or below	175	13%
	2-3 years of College	380	29%
	Undergraduate or above	775	58%
Personal monthly income (CNY)	<3,000	73	6%
	3,000-4,999	110	8%
	5,000–6,999	300	23%
	7,000–9,999	404	30%
	>10,000	443	33%

3.3 Data analysis procedure

Descriptive analyses were initially conducted to provide an overview of research respondents' responses to GM and SB applied to food production and different SB food applications. The thoughts or images evoked by three SB applications were categorized into different themes, which were connected to positive and negative affect. Subsequently, a comparative analysis of the respondents' responses to SB and its different applications was conducted. The Mann–Whitney *U* test and the Kruskal-Wallis test were used to compare respondent responses across gender and educational levels, respectively. One-way ANOVA with repeated measures was used to compare respondents' acceptance of the three SB food applications. The relationship between the respondents' prior attitudes towards GM food and their general attitudes towards SB food was examined via zero-order (i.e., the original bivariate correlation) and partial correlations (i.e. the correlation controlling for individuals' food technology neophobia, "balance of nature" and "human domination" environmental worldviews). The paired sample t-test was used to compare respondents' attitudes towards GM food and SB food. All the above data analysis process was conducted using IBM SPSS Statistics Version 24.

Finally, partial least squares structural equation modelling (PLS-SEM) was employed to estimate the proposed model. We chose PLS-SEM rather than covariance-based structural equation modelling (CB-PLS) because the research was intended to explore an extension of the "risk-benefit-acceptance" model for better explaining public acceptance of SB food applications rather than test an existing theory, which made PLS-SEM a more suitable methodology (Hair et al., 2017). To ensure the reliability and validity of the measurement models, different criteria were used: Cronbach's alpha $\alpha > 0.7$ and composite reliability $\rho > 0.7$; values of average variance extracted (AVE) > 0.5; and an indicator's outer loadings on a construct being higher than its outer loadings with other constructs, the application of Fornell-Larcker Criterion (the square root of the AVE of each construct being higher than its highest correlation with any other construct), and the heterotrait-monotrait ratio (HTMT) < 0.9 (Hair et al., 2017). The structural model was evaluated by testing the collinearity between constructs, the significance and relevance of model relationships, coefficients of determination (adjusted R^2), an exogenous construct's contribution to an endogenous latent variable's R^2 value using the effect size f^2, and the predictive relevance (Stone-Geisser's Q^2) (Hair et al., 2017; Rigdon, 2012; Stone, 1974). A standardized root mean square residual (SRMR) of estimated models being smaller than 0.08 was selected as a conservative criterion for ensuring the model fit for PLS-SEM (Henseler et al., 2014; Hu & Bentler, 1998).

Notably, the goodness of fit (GoF), which has been used to measure model fit for CB-SEM, was not chosen as a measure of the model fit because it is unable to identify misspecified models (Henseler et al., 2014). PLS-SEM was conducted using SmartPLS3 (Ringle et al., 2015).

4. RESULTS

This section addresses the three research questions (RQ) proposed in Section 1, including the relationship between respondents' prior attitudes towards GM food and general attitudes towards SB food (RQ1); responses to three SB agri-food applications (RQ2); and influence of different factors on acceptability of SB applications (RQ3).

4.1 Attitudes towards GM food and SB food

The results showed that the respondents held slightly positive attitudes towards GM food (M = 3.13, SD = 0.83, Cronbach's alpha = 0.72) and SB food (M = 3.27, SD = 0.81, Cronbach's alpha = 0.79). Attitudes towards SB food were significantly more positive than GM food (paired sample t-test; t = 6.59, p < 0.001). The zero-order correlation between the respondents' prior attitudes towards GM food and their general attitudes towards SB food was 0.53 (p < 0.001). The partial correlation between the two factors, i.e. controlling for individuals' food technology neophobia (Cronbach's alpha = 0.81), "balance of nature" (Cronbach's alpha = 0.72) and "human domination" (Cronbach's alpha = 0.75) environmental worldviews), was 0.50 (p < 0.001). Thus, hypothesis 5 was supported. Both strong positive zero-order and partial correlations implied that respondents' prior attitudes towards GM food positively predicted their general attitudes towards SB food.

4.2 Responses to SB food applications

Repeated-measures ANOVA with a Greenhouse-Geisser correction were conducted to compare the survey respondents' responses to SB foods (see Table 2). In terms of different

SB food applications, food produced using the SB soybean (M = 3.41, SD = 0.87, Cronbach's alpha = 0.78) was associated with the highest level of acceptance, followed by that using the SB yeast (M = 3.18 SD = 0.89, Cronbach's alpha = 0.79). Food produced using the SB pig (M = 2.94, SD = 1.00, Cronbach's alpha = 0.83) was the least accepted. The mean acceptance levels differed significantly between three applications [F (1.899, 2523.394) = 198.046, p < 0.001]. *Post hoc* tests using a Bonferroni correction indicated that the acceptance level of the SB soybean was 0.234 higher than that of the SB yeast (p < 0.001), 0.472 higher than that of the SB pig (p < 0.001), and that the acceptance level of the SB yeast was 0.238 higher than that of the SB pig (p < 0.001).

The results of repeated-measures ANOVA with a Greenhouse-Geisser correction also showed significant differences in affect, perceived benefits, perceived unnaturalness, and perceived risks between the applications. The perceived benefits associated with the SB soybean were significantly higher than that of SB yeast and that of the SB pig, and the perceived benefits of SB yeast were significantly higher than that of the SB pig (see Table 2). The perceived unnaturalness and perceived risks associated with the SB soybean were significantly lower than those of SB yeast and the SB pig, and the perceived unnaturalness and perceived risks associated with SB yeast were significantly lower than those associated with the SB pig. The SB yeast and SB pig both evoked negative affect, with SB yeast being significantly more negative, while the SB soybean evoked relatively positive affect (Table 2). The Mann–Whitney U test and the Kruskal-Wallis test showed that there was no significant difference in respondents' general attitudes towards SB food and their acceptance of the three SB food applications across gender and educational level (details see Supplementary Material Section One, Table B and C).

The affective responses evoked by the SB yeast, the SB soybean and the SB pig were categorized into nine, ten and thirteen themes (Supplementary Material Section One, Table

D), accounting for 91%, 86% and 86% of respondents' responses, respectively. The three most frequently evoked themes associated with the SB yeast were all categorized as evoking negative affect (i.e. the value of affect was smaller than 4), accounting for 52% of the responses. Of the different themes, only "information seeking" and "the perceived increased productivity and reduced price of dairy products" were connected to positive affect (i.e. the value of affect was larger than 4), which accounted for 5% and 4% of the responses, respectively.

In contrast, the four most frequently evoked themes associated with the SB soybean comprised 56% of the responses (Supplementary Material Section One, Table D), which were connected to positive affect. Only three themes (i.e. "the perceived health effect of eating SB soybean-based food", "regarding GM food as a similar kind of product" and "overall rejection of the SB soybean") were associated with negative affect, accounting for 13% of the responses. The five most frequently evoked themes associated with the SB pig were all associated with negative affect, except for "the perceived increased productivity and reduced price of SB pork". Respondents' emotional reactions, "fear, worry or hesitation" (5%) and "feeling weird or disgusting" (1%), were associated with the highest magnitude of negative affect.

Table 2. Respondents' acceptance of SB food applications

Constructs	Mean (Standard Deviation)			Repeated Measures ANOVA	Post Hoc Test (Bonferroni)		
	App 1: SB yeast	**App 2: SB soybean**	**App 3: SB pig**		**Comparison between applications**	**Mean difference**	**p value**
Affect	3.53 (1.08)	4.50 (1.20)	3.71 (1.38)	F (2, 2657.418) = 366.966 $p < 0.001$	App 1 *VS* App 2	-0.973	$p < 0.001$
					App 1 *VS* App 3	-0.183	$p < 0.001$
					App 2 *VS* App 3	0.790	$p < 0.001$
Perceived benefits	3.27 (0.74)	3.51 (0.72)	3.11 (0.79)	F (1.908, 2535.976) = 211.332 $p < 0.001$	App 1 *VS* App 2	-0.231	$p < 0.001$
					App 1 *VS* App 3	0.165	$p < 0.001$
					App 2 *VS* App 3	0.396	$p < 0.001$
Perceived unnaturalness	3.28 (1.08)	3.15 (1.13)	3.38 (1.14)	F (2, 2629.095) = 25.068 $p < 0.001$	App 1 *VS* App 2	0.138	$p < 0.001$
					App 1 *VS* App 3	-0.100	$p < 0.01$
					App 2 *VS* App 3	-0.238	$p < 0.001$
Perceived risks	3.16 (0.74)	3.03 (0.79)	3.33 (0.81)	F (1.902, 2527.286) = 134.553 $p < 0.001$	App 1 *VS* App 2	0.125	$p < 0.001$
					App 1 *VS* App 3	-0.175	$p < 0.001$
					App 2 *VS* App 3	-0.299	$p < 0.001$
Acceptability	3.18 (0.89)	3.41 (0.87)	2.94 (1.00)	F (1.899, 2523.394) = 198.046 $p < 0.001$	App 1 *VS* App 2	-0.234	$p < 0.001$
					App 1 *VS* App 3	0.238	$p < 0.001$
					App 2 *VS* App 3	0.472	$p < 0.001$

Note: Affect was rated using a seven-point scale ranging from 1 = "extremely negative" to 7 = "extremely positive", and the others using five-point Likert scales (1 = "strongly disagree" to 5 = "strongly agree"). $p < 0.05$ means the Repeated Measures ANOVA or Post Hoc Test (Bonferroni) test is statistically significant.

4.3 Results of PLS-SEM related to attitude formation

4.3.1 Evaluations of the model

All reliability and validity criteria were met for the measurement models for each SB food application (see Supplementary Material Section One, Table E and F). The values of SRMR were all smaller than 0.08, showing a good model fit across applications (Supplementary Material Section One, Table G). All the variance inflation factor (VIF) values were smaller than 5, indicating that there were no critical collinearity problems between the assessed constructs (Supplementary Material Section One, Table H). The model had a satisfactory level for explaining respondents' acceptance of SB food applications, where the adjusted R^2 values for acceptance were 0.544 for the SB yeast, 0.533 for the SB soybean, and 0.623 for the SB pig (Falk & Miller, 1992). Stone-Geisser's Q^2 values were larger than 0 (Supplementary Material Section One, Table I), representing satisfactory predictive relevance (Stone, 1974).

Standardized values of path coefficients β, the respective *t*-values, 95% confidence intervals and f^2 were also obtained (see Table 3). Here, the t value > 1.96 (two-tailed tests, significance level = 5%) and p-value < 0.05 represent a significant correlation between two variables. All the hypotheses were supported in the model across different SB applications. The total indirect effects of general attitudes towards SB food, affective reaction and perceived unnaturalness on application acceptance are presented in Supplementary Material Section One, Table J. The mediation effects of the respondents' affective reactions, evaluation of risks, benefits and food unnaturalness associated with specific SB food applications on the relationship between their attitudes towards SB food in general and acceptance of those SB food applications were tested. The standardized values of path coefficients β, the respective *t*-values, 95% confidence intervals and v^2 (effect size of indirect effects) are shown in Table 4.

4.3.2 Key findings of PLS-SEM

The key findings of PLS-SEM across the three SB food applications are presented in Table 5. In order to better compare the power (total effects) of different factors that could explain the respondents' perceptions and acceptance of different SB food applications, effect size f^2 was selected as a suitable indicator (Hair et al., 2017), where the values of 0.02, 0.15 and 0.35 represent a small, medium and large effect, respectively (Cohen, 1988). In terms of mediation analysis (specific indirect effects), effect size v^2 was selected as a suitable indicator of impacts, where the values of 0.01, 0.04 and 0.09 represent a small, medium and large effect, respectively (Gaskin et al., 2023).

Table 3. Estimation results of the model across SB applications

Hypotheses		SB yeast				SB soybean				SB pig			
		β	***t* values**	***f*²**	**95% CI**	**β**	***t* values**	***f*²**	**95% CI**	**β**	***t* values**	***f*²**	**95% CI**
H1a	PR -> AA	-0.163***	6.096	0.035	[-0.213, -0.109]	-0.161***	5.506	0.033	[-0.218, -0.103]	-0.125***	4,974	0.021	[-0.172, -0.073]
H1b	PB -> AA	0.424***	15.858	0.258	[0.371, 0.474]	0.392***	13.013	0.204	[0.333, 0.451]	0.356***	13,233	0.176	[0.304, 0.409]
H2a	PU -> PR	0.543***	25.860	0.457	[0.500, 0.582]	0.501***	21.011	0.396	[0.453, 0.547]	0.506***	20,281	0.416	[0.456, 0.554]
H2b	PU -> PB	-0.083**	3.085	0.010	[-0.135, -0.030]	-0.067**	2.647	0.007	[-0.117, -0.019]	-0.082**	3,328	0.011	[-0.131, -0.035]
H2c	PU -> AA	-0.093**	3.441	0.012	[-0.147, -0.041]	-0.066*	2.411	0.006	[-0.119, -0.013]	-0.053*	2,246	0.004	[-0.101, -0.009]
H3a	Affect -> PR	-0.124***	5.170	0.023	[-0.171, -0.076]	-0.189***	6.776	0.050	[-0.242, -0.133]	-0.295***	10,315	0.128	[-0.350, -0.238]
H3b	Affect -> AA	0.141***	6.504	0.038	[0.098, 0.183]	0.180***	6.076	0.045	[0.120, 0.236]	0.315***	12,441	0.142	[0.266, 0.365]
H3c	Affect -> PB	0.181***	7.122	0.045	[0.130, 0.230]	0.403***	15.581	0.215	[0.350, 0.450]	0.483***	19,202	0.334	[0.433, 0.532]
H3d	Affect -> PU	-0.148***	4.846	0.022	[-0.209, -0.089]	-0.210***	6.408	0.041	[-0.273, -0.144]	-0.355***	12,005	0.129	[-0.412, -0.296]
H4a	GA -> Affect	0.248***	7.921	0.066	[0.186, 0.308]	0.387***	13.385	0.176	[0.328, 0.439]	0.377***	13,925	0.166	[0.324, 0.430]
H4b	GA -> PU	-0.180***	5.585	0.033	[-0.242, -0.118]	-0.123***	3.693	0.014	[-0.187, -0.057]	-0.092**	3,092	0.009	[-0.149, -0.032]
H4c	GA -> PR	-0.140***	5.416	0.030	[-0.190, -0.088]	-0.157***	5.695	0.035	[-0.210, -0.103]	-0.048*	1,978	0.004	[-0.096, -0.001]
H4d	GA -> PB	0.481***	18.658	0.317	[0.426, 0.528]	0.312***	11.947	0.132	[0.261, 0.363]	0.288***	11,074	0.133	[0.238, 0.340]
H4e	GA -> AA	0.204***	7.368	0.062	[0.150, 0.259]	0.180***	6.464	0.050	[0.127, 0.237]	0.152***	6,457	0.046	[0.105, 0.198]

Note: The asterisks refer to significance levels of the path coefficients between the constructs included in the model based on bootstrapping: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. β = path coefficients; 95% CI = 95% confidence interval; GA = general attitudes towards SB applied to food production; PB = perceived benefit; PR = perceived risk; PU = perceived unnaturalness; AA = acceptance of the application.

Table 4. Mediation analyses of the relationship between general attitudes and SB application acceptance

Mediation pathway	**SB yeast**				**SB soybean**				**SB pig**			
	β	***t* values**	v^2	**95% CI**	**β**	***t* values**	v^2	**95% CI**	**β**	***t* values**	v^2	**95% CI**
GA -> Affect -> AA	0.031***	3.641	0.001	[0.015, 0.049]	0.014	0.682	0	[-0.027, 0.050]	0.109***	6.691	**0.012**	[0.078, 0.142]
GA -> PU -> AA	0.013	1.679	0	[-0.002, 0.028]	0.002	0.315	0	[-0.011, 0.013]	0.004	1.027	0	[-0.003, 0.011]
GA -> PB -> AA	0.375***	9.707	**0.143**	[0.307, 0.459]	0.303***	7.074	**0.094**	[0.229, 0.396]	0.181***	7.731	**0.033**	[0.139, 0.230]
GA -> PR -> AA	0.036***	3.663	0.001	[0.019, 0.057]	0.046***	3.569	0.002	[0.024, 0.074]	0.009	1.799	0	[0, 0.020]

Note: The asterisks refer to significance levels of the path coefficients between the constructs included in the model based on bootstrapping: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. The values of the effect size v^2 over 0.01 are presented in bold, indicating non-negligible mediation effects. β = path coefficients; 95% CI = 95% confidence interval; GA = general attitudes towards SB applied to food production; PB = perceived benefit; PR = perceived risk; PU = perceived unnaturalness; AA = acceptance of the application.

Table 5. Key findings of PLS-SEM across SB applications

Themes	**Relevant constructs**	**Results of the present research**	**Comparison of constructs and applications**	**Summary**
Total impacts on application acceptance	General attitudes towards SB food; affect; perceived benefit; perceived risk; perceived unnaturalness; application acceptance	The perceived benefit had medium positive effects (f^2 ranging from 0.176 to 0.258), while the perceived risk (f^2 ranging from 0.021 to 0.035) had small negative effects on the acceptability of SB applications. General attitudes (f^2 ranging from 0.046 to 0.062) and affect (f^2 ranging from 0.038 to 0.142) had small positive effects on the acceptability of SB applications. The perceived unnaturalness had very limited negative effect on the acceptability (f^2 ranging from 0.004 to 0.012), despite the significant relationships.	Of the different factors included in the proposed model, benefit perceptions were the most influential in affecting acceptability. The influence of affect on respondents' acceptance was larger for the SB pig compared to SB yeast (f^2 = 0.038) and SB soybean (f^2 = 0.045), indicating almost a medium impact (f^2 = 0.142), close to the impact of the perceived benefit (f^2 = 0.162).	General attitudes towards SB food, affect, perceived benefit and perceived risk associated with an SB food application shaped Chinese respondents' acceptance of this application, despite their different degrees of impact. The impact of perceived unnaturalness on acceptability was almost negligible.

Direct and indirect impacts on application acceptance	General attitudes towards SB food; affect; application acceptance	The direct (β ranging from 0.141 to 0.315) and indirect impacts (β ranging from 0.129 to 0.261) of affect on acceptability were similar across applications. General attitudes towards SB food had bigger indirect impacts (β ranging from 0.325 to 0.339) on acceptability compared to the direct impacts (β ranging from 0.152 to 0.204).	In contrast to affect, general attitudes tended to affect acceptability in a more indirect way. The biggest direct impact of affect on acceptability was for SB pig.	Having both significant direct and indirect impacts on acceptability, general attitudes tended to affect acceptability more indirectly, while the direct and indirect impacts of affect were relatively equal.
	General attitudes towards SB food; affect; perceived unnaturalness; perceived benefit; perceived risk; application acceptance	Affect had a small mediating effect on the relationship between general attitudes towards SB food and application acceptance for the SB pig (v^2 = 0.012). Perceived benefits had large mediating effects for SB yeast and the SB soybean (v^2 > 0.09), and a small mediating effect for the SB pig (v^2 = 0.033) on the relationship between general attitudes towards SB food and application acceptance.	The relationship between general attitudes towards SB food and application acceptance is more likely to be mediated by perceived benefit compared to the other factors.	Positive general attitudes towards SB food can indirectly increase respondents' acceptance of different SB food applications *via* increasing their relevant benefit perceptions.
Interrelationships between constructs	Perceived unnaturalness; perceived benefit; perceived risk	Perceived unnaturalness had large positive impacts on perceived risk (f^2 ranging from 0.396 to 0.457), but very limited negative impact on perceived benefit (f^2 ranging from 0.007 to 0.011).	Perceived unnaturalness had much bigger impacts on perceived risk than on perceived benefit across applications.	Perceived unnaturalness is a strong predictor of perceived risk but not of perceived benefit.

Affect, perceived unnaturalness; perceived benefit; perceived risk	Affect had positive impacts on perceived benefit (f^2 ranging from 0.045 to 0.334) and negative impacts on perceived unnaturalness (f^2 ranging from 0.022 to 0.129) and perceived risk (f^2 ranging from 0.023 to 0.128) across applications.	Affective reaction had larger impacts on perceived benefit than on perceived unnaturalness and perceived risk across applications. Affect had the largest impacts on perceived benefit, perceived unnaturalness and perceived risk for the SB pig.	Respondents' perceived benefit was more affect-based compared to their perceived unnaturalness and risk of an SB food application. Judging risk, benefit and unnaturalness of animal-based SB applications may engage more experiential thinking compared to those based on plants and microbes.
General attitudes towards SB food; affect, perceived unnaturalness; perceived benefit; perceived risk	General attitudes towards SB food had positive impacts on affect (f^2 ranging from 0.066 to 0.176) and perceived benefit (f^2 ranging from 0.132 to 0.317) and negative impacts on perceived unnaturalness (f^2 ranging from 0.009 to 0.033) and perceived risk (f^2 ranging from 0.004 to 0.035).	General attitudes had larger impacts on affect and perceived benefit than on perceived unnaturalness and perceived risk across applications. The negative impacts of general attitudes on perceived unnaturalness and perceived risk were very limited for SB pig.	General attitudes towards SB food can affect how Chinese respondents interpret the provided information about specific SB food applications, thereby influencing their affective reactions and judgements of relevant risks, benefits and unnaturalness.

5. DISCUSSION

5.1 General attitudes towards GM food and SB food

The results indicated that, Chinese respondents' attitudes towards SB applied to food production are more positive than those towards GM food. Previous research has also indicated more positive attitudes towards gene-edited food than GM food among Chinese and US consumers (Ortega et al., 2022; Shew et al., 2018). As such, the Chinese public may be more sensitive about inserting foreign genes from other species to a host organism compared with inserting artificial genes/genome to, or just removing target genes from the host organism. Some researchers have reported more negative public attitudes towards SB applications within the agri-food sector compared to the other sectors, such as energy and health (Pauwels, 2013; Steurer, 2015). Chinese natural scientists have also predicted the emergence of societal resistance to the application of SB to food production (Jin et al., 2021). However, the results presented here suggest that, in China, acceptance of SB food applications is nuanced by people's perceptions of specific application attributes, showing the potential misunderstanding of public attitudes towards SB food among Chinese natural scientists. This might relate to more frequent discussion of the public's strong resistance to, rather than support of, agri-food biotechnology on Chinese social media (Ji et al., 2019). At the same time there is a disconnect between natural scientists and the public that inhibits two-way communication in particular regarding exchanging opinions on specific agri-food applications (Jin et al., 2021).

5.2 Public perceptions of specific SB food applications

The analysis indicated that Chinese respondents' perceptions and attitudes vary by application type, with an overall acceptance of SB soybean and SB yeast, but overall rejection of the SB pig. Such attitudinal differences may result from the combined influence of different application attributes, such as the host organisms to which the technology is applied, and the traits of the application that relate to people's different perceived risks, benefits and ethical concerns. Application-specific attitudes may differ by region due to different preferences for application traits. For example, price discounts and improved nutritional content of GM food compared to conventional food resulted in positive impacts on US consumer acceptance of GM food (Lusk et al., 2015), whereas no significant impact of nutritional content and even a negative impact of price discount on consumer attitudes were identified based on a meta-analysis of 214 studies conducted in different regions of the world (Hess et al., 2016).

An interesting finding in the research presented here was that greater negative affect was evoked by the SB yeast for milk protein than by the SB pig with improved immune function. This might be because milk is often naturally produced by animals and using the SB yeast for milk protein might represent a radical change for Chinese respondents. Another reason may relate to Chinese people still harboring worries about dairy products-related innovations subsequent to the 2008 Chinese milk scandal, where milk and infant formula were adulterated with melamine. Due to the toxic effects of melamine, there was an estimated 300,000 victims, including 860 children hospitalized and six infants dying from kidney damage (Zhou & Wang, 2011)). The safety and quality of dairy products in China are still of public concern (Gossner et al., 2009; Kendall et al., 2019; Yang et al., 2018). Despite this, respondents still perceived a higher level of benefits than risks associated with the SB yeast for producing milk protein and expressed overall positive intentions to drink the milk produced by using this process.

In contrast, Swiss consumers perceived the same SB yeast to be of high risk and low benefit, leading to a very low level of acceptance (Egolf et al., 2019). One reason for the attitudinal difference might relate to Europeans holding more negative attitudes towards applying biotechnology to food production (e.g. GM food) than Asian consumers (Frewer et al., 2013; Woźniak et al., 2021). Another reason could be that the participants have been primed by the labels used in the experimental design (Egolf et al., 2019): "artificial milk" in the Swiss study versus "novel milk" in the research presented here. The label of "artificial milk" in itself might have evoked a higher level of disgust and/or perceived unnaturalness (Rozin et al., 2004), thereby resulting in higher risk perceptions and lower acceptance. Future research into people's responses to specific SB food applications, or indeed other applications of technology to food production, needs to consider the potential framing effect in the development of product/application information (Bryant & Barnett, 2019; Tversky & Kahneman, 1981)).

5.3 Driver of public acceptance of SB food applications

The results of the present research indicated that Chinese respondents' acceptance of SB food applications is driven by a combination of multiple factors. These factors interacted with each other and showed different impacts on application acceptance. For instance, perceived unnaturalness was a strong predictor of Chinese respondents' risk perceptions of different SB food applications. However, this factor had a very limited effect on acceptability (see also Jin et al., 2022), in which a similar relation was observed for GM foods. This was inconsistent with some findings from research conducted in Western countries, in particular those focused on peoples' acceptance of GM food (Mielby, Sandøe, & Lassen, 2013; Siegrist et al., 2016; Tenbült, De Vries, Dreezens, & Martijn, 2005). One study examining attitudes towards cultured meat also showed that the impact of perceived naturalness on acceptability is smaller for Chinese consumers compared to French, Australian, German, Spanish and US consumers (Siegrist & Hartmann, 2020b). As the impact of perceived unnaturalness on the acceptability of food technologies has been infrequently investigated within China, future research should further investigate whether this is a stable difference across geographic regions and distinct technologies. If the difference is robust, then the causes should also be investigated.

Previous research suggested that people's affective reactions evoked by a technology contribute to people's risk and benefit perceptions (Alhakami & Slovic, 1994). The results also found that Chinese respondents' affective reactions to an SB food application have positive and negative impacts on their acceptance of the application, respectively. The impacts of affective reactions on benefits perceptions associated with SB applications were much larger than those on risk perceptions, as has been reported in previous research focused on people's responses to GM (Jin et al., 2022) and nanotechnology foods (Siegrist et al., 2007). This implies that benefit perceptions in this context are more likely to be derived from experiential thinking (e.g. affective/heuristic information processing) compared to risk perceptions. Indeed, food-related benefit and risk perceptions have been reported to be more likely to be derived from experiential thinking (heuristic information processing and personal experience) and deliberative information processing, respectively (Fischer & Frewer, 2009).

5.4 Policy implications

In the research presented here, it has been shown that significant attitudinal differences across SB agri-food applications. Thus, it is unlikely, or inappropriate, to assume that the most efficacious way to progress regulatory frameworks is to develop a governance structure that treats all agri-food applications that are derived from GM, SB and genome editing being governed under a single regulation for GM (e.g., EU Directive 2001/18/EC[6] and 2009/41/EC[7], and "Regulations on Administration of Agricultural Genetically Modified

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32001L0018 (accessed 20 June 2021).

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009L0041 (accessed 20 June 2021).

Organisms Safety”[8] in China). This is because such a blanket policy might enhance public sense-making of novel biotechnologies applied to the agri-food sector all by anchoring previous attitudes towards GM food. Consequently, stronger societal concerns may emerge particularly within cultures that tend to be more anti-GM and regulate food technologies on the basis of risk avoidance. For instance, despite both depending on their prior GM food-related attitudes to make sense of SB food, Austrian people’s general attitudes towards SB food were more negative than their existing attitudes towards GM food (Steurer, 2015), while we found that Chinese consumers’ general attitudes towards SB food were more positive than their attitudes towards GM food. Different host organisms and new traits derived from SB applications could also be considered differently by the public. Future research should further investigate the public’s preferred and prioritized SB agri-food applications and directly engage the public regarding their policy priorities.

Despite SB applications potentially benefiting food security and environmental sustainability, rigorous risk assessment, management and communication are still required at all stages of the commercialization trajectory to protect public interests. This process must take account of public perceptions and concerns, including those related to ethical issues (König et al., 2010). First, understanding what characteristics consumers require from SB food in a specific social context, if any, will ensure effective collaboration between society and science in relation to agri-food technology development. This would help identify risks that are of public concern and to focus mitigation and communication strategies on these risks. For example, in China, research and development investment in the public and private sectors might prioritize developments that utilize plants as host organisms rather than animals. Applications with direct and multiple benefits for consumers, or the environment, as opposed to the economy, might also be prioritized over those with economic benefits alone.

[8] http://www.moa.gov.cn/ztzl/zjyqwgz/zcfg/201007/t20100717_1601306.htm (accessed 20 June 2021).

The development of dairy-related SB applications may need to proceed with caution, at least in China, due to the milk scandal. Second, the development of information about societal preferences for SB products in particular, and emerging food technologies in general, should occur early enough for the public to be able to contribute towards the codesign of product development. This will ensure that the public can influence the final product design and provide evidence for policy formulation. Product developers, including those within the scientific community, and policymakers should be trained in conducting or sponsoring relevant co-production methodologies, and the need to address societal priorities as well as technical possibilities, when considering the route to commercialization of SB products. Such a transparent process may catalyze more positive societal attitudes towards SB food in general, which can potentially increase people's acceptance of specific applications directly and indirectly (*via* increasing their benefit perceptions). Third, people's affective reactions to (information about) specific applications need to be considered in risk communication. This is because the communication itself may evoke an affective reaction in the message recipient, rather than triggering further deliberative analysis, which might be the goal of such communication. Provoking certain affective reactions could have unintended impacts on the recipients' risk and benefit perceptions and, consequently, their acceptance of specific applications. Fourth, as there exists discrepancy between SB product developers' (e.g. scientists) prediction of social reactions and consumers' actual responses to SB (Jin et al., 2021), it may be appropriate to exchange knowledge between different stakeholder constituencies about how to communicate SB-related information. Communication mechanisms between the public, scientists, industries, government representatives and other broader stakeholders should be established to co-develop not only the products but also the information for risk and benefit communication. In turn, this could increase the transparency, openness, and accountability of the risk and benefit management processes for SB agri-food applications.

5.5 Limitations and future research

There are limitations associated with the sampling method, the research design and the proposed model. The survey respondents were recruited from Tier 1 and Tier 2 cities and tended to be younger and more educated than Chinese public in general. Also, using online surveys for data collection might have excluded those who have limited access to the internet. As such, the results of the present research may not be generalizable to the whole Chinese population. Future research should address this limitation by selecting more nationally representative participants.

Despite efforts to provide the research participants with neutral information, the framing effect still exists. Different framings of SB and its applications may cause people to develop distinct attitudes (Bryant & Dillard, 2019; Siegrist & Hartmann, 2020b). Also, the introduction to SB and its applications in our survey included limited information regarding technical details to make it easier for the participants to understand and engage with what information was provided, which, however, might have compromised the participants' distinguishing SB from GM. As the public become more familiar with SB, future research could provide more technical details (including those related to whole-genome synthesis) to research participants to build upon on their knowledge about SB technology (Rogers, 2011).

Another limitation relates to the use of application attributes-related statements to test respondents' risk and benefit perceptions. Such a design can better guide the future development and commercialization of the applications under consideration, and applying SB to food production more generally. However, the specificity of the benefits and risks might not be immediately relevant or understandable for some respondents due to their relatively higher complexity compared to the general risk and benefit statements without considering application attributes (e.g. SB yeast may result in risks/benefits to the environment/human health), which might have led to the increased measurement error especially among the older and less-educated respondents (Holbrook et al., 2006; Lenzner, 2014). As an example, in the case of the SB yeast, its environmental benefit due to the reduced land use and carbon dioxide emissions compared to traditional dairy production might be not understandable for some respondents or irrelevant to their benefit perception (e.g. because of their relatively low concern about negative environmental impacts caused by food production) (Jin et al., 2023). This has partly explained the internal inconsistency of the benefit perception construct for the SB yeast caused by the environmental benefit-related statement, which has thus been removed from the modeling (Table A). Given the relatively young and well-educated respondents in our survey and the high understandability of the SB applications-related information (over 90% of the respondents indicated that the texts about three SB applications were understandable to them; for details see the follow-up survey report in Supplementary Material Section Two), the magnitude of the measurement error should be small in the present study. However, it could be problematic if using the findings to predict older and less-educated Chinese people’s responses to SB food. To address this, future research should, on the one hand, engage older and low-educated people to co-design the survey questions (including these risk and benefit statements) to ensure understandability and relevance, and on the other hand, include general risk and benefit statements without considering application attributes in the survey for measurement validation.

Due to the non-randomized survey design (e.g. the fixed order of three SB applications and always presenting benefits-related statements before risk-related statements for each application), there could be biased results related to the roles of the respondents’ general attitudes towards SB food and risk perceptions in affecting their SB application acceptance.

Although the follow-up survey indicated no significant biases related to those (details see Supplementary Material Section Two), randomization in survey design would improve the methodological design in future research. Some differences occurred in the follow-up survey in terms of the roles of respondents' affective responses and benefit perceptions in affecting their application acceptance. This has raised the need to further explore factors that have resulted in those differences, such as the different socio-demographic attributes of the respondents included the two surveys and changes in social contextual factors due to the different timing of survey data collection. For example, at the early stage of the COVID-19 pandemic, the Chinese participants could be more risk averse when making food-related decisions due to, for example, the news about COVID-19 transmissibility through food supply chains, and a more negative affective state (e.g. state anxiety) that can be generalized to affective responses in general (Cantalapiedra et al., 2022; Laguna et al., 2020; Sobkow et al., 2016; Tian et al., 2020). At a later stage of the COVID-19 pandemic, Chinese people may have lower risk perceptions and higher acceptance of SB foods than those measured here due to the news about the non-existent or minor COVID-19 transmissibility through food supply chains and a less negative affective state (The European Food Safety Authority, 2020), as has been found through the comparison between the present survey and the follow-up survey (see Supplementary Material Section Two). As such, regular monitoring of public responses to SB foods is needed in future research, in which both socio-economic attributes of the respondents and social contextual factors (e.g. social trust, regional and national food incidents) should also be considered at different time points (Miao et al., 2020).

Another limitation relates to the direction of the influence between affect and perceived unnaturalness within our proposed model. Despite having provided evidence for the assumption that Chinese respondents' affective reaction precedes their perceived unnaturalness of an SB food application based on previous research (Jin et al., 2022), the results still could not directly confirm the direction of the influence. In particular, the two directions may coexist within the population, which can potentially be influenced by, for example, individuals' knowledge about SB food and perceived importance of food naturalness (Greene & Haidt, 2002; Siegrist & Hartmann, 2020a; Wilks et al., 2021). This limitation should be addressed in future research in consideration of the potential effects of individual and cultural heterogeneity, as well as different research conditions (e.g. the selected food products) on the directionality, which appears to be a fruitful topic for future research. Mediating effects (e.g. related to general attitudes towards SB food) as well as the potential differences by application type and cultural context should also be further explored and validated to facilitate the understanding of SB application-specific attitudes formation.

6. CONCLUSION

It has shown Chinese respondents' significant attitudinal differences across three SB agri-food applications in the present research, implying that applications developed to improve food security and simultaneously reduce negative environmental impacts may be more societally acceptable. The factors that shape application acceptability were also identified, of which benefit perceptions were the most influential. Respondents' affect evoked by exposure to information of SB applications had variant effects on the acceptability across application types, with the largest impact for the animal-based application. Respondents' general attitudes towards SB food were predicted well by their prior attitudes towards GM food and had small but significant impacts on the acceptability of specific SB food applications. The findings of the present research have implications for the development of policy that can effectively regulate and develop SB within the agri-food sector. At the same time, potential differences in peoples' responses to SB agri-food applications across countries suggest that more international research and governance collaborations are needed to establish and implement governance and regulation of different SB agri-food products at a global scale, because SB, together with other technologies, represent a transboundary risk which cannot be contained within geographic or political regions.

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