Trends in Food Science & Technology 91 (2019) 454–466

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Review

Synthetic biology applied in the agrifood sector: Public perceptions, attitudes and implications for future studies

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ARTICLE INFO

Keywords:
Synthetic biology
Food
Agriculture
Public perception
Public attitude
Mapping review

ABSTRACT

Background: Synthetic biology is an emerging multidisciplinary area of research with the potential to deliver various novel agrifood applications. Its long-term adoption and commercialisation will depend on the extent to which the public accept synthetic biology and its different applications.
Scope and approach: A mapping review of existing research on public perceptions of, and attitudes towards, synthetic biology and its applications to agriculture and food production was conducted. This enabled an overview of current knowledge about public perceptions and attitudes to be developed, and current research gaps to be identified.
Key findings and conclusions: Although some risk-related and ethical concerns were raised by the public, there was little evidence showing that people had an inherently negative perception of synthetic biology. The results demonstrated the importance of perceived benefits, perceived risks and ethical issues in shaping public acceptance of synthetic biology applied to agrifood production. Where analysis focused on specific applications, people tended to be more positive about medical and environmental applications compared to those in the agrifood sector. This is also the case for other areas of technology application, such as nanotechnology and genetic modification. However, at present, the literature is focused on synthetic biology as an enabling technology rather than on its specific applications. Given some evidence that people's attitudes varied by product types, more research on specific applications is therefore needed to further investigate public attitudes and co-develop societal preferences for agrifood products.

1. Introduction

Synthetic biology is a novel multidisciplinary area of research that has attracted considerable academic attention due to its numerous potential applications across different domains (e.g. in medicine, material science and agriculture, *inter alia*) (Benner & Sismour, 2005). In common with other emerging technologies, such as nanotechnology, there is no standardised definition available to date. The European Commission (2005) has defined synthetic biology as "applying the engineering paradigm of systems design to biological systems in order to produce predictable and robust systems with novel functionalities that do not exist in nature" (p. 10). The Royal Academy of Engineering (2009) has proposed that synthetic biology involves "the design and construction of novel artificial biological pathways, organisms and devices, or the redesign of existing natural biological systems" (p. 13). Alternatively, synthetic biology can be described as "the design and construction of new biological parts, devices, and systems, and the redesign of existing, natural biological systems for useful purposes" (Springer Nature, 2019). All definitions encompass the notion that applications of synthetic biology involve the creation of novel living systems through synthesising and assembling artificial and/or natural components.

There are both technology and application differences between synthetic biology and genetic modification (GM). Synthetic biology constructs living systems by synthesising and assembling DNA according to engineering principles (Cameron, Bashor, & Collins, 2014), whilst GM simply inserts a piece of foreign DNA into host organisms to produce desired traits (Colwell, Norse, Pimentel, Sharples, & Simberloff, 1985). Consequently, synthetic biology may involve the use of larger amounts of DNA, which can be naturally occurring or synthetic, and the constructed parts could be standardised and shared within the community to establish more complex systems (Cameron et al., 2014). The sharing and rebuilding based on standardised living systems could facilitate the development of new applications, but may

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https://doi.org/10.1016/j.tifs.2019.07.025
Received 6 December 2018; Received in revised form 25 March 2019; Accepted 17 July 2019
Available online 24 July 2019
0924-2244/

Table 1
Applications of synthetic biology in the agrifood sector.

Area of application		Host	Traits/product	Examples	Stage	References
Agriculture	Crop improvement	Plant	Productivity increase	Improved carbon fixation in crops.	Laboratory	Bar-Even, Noor, Lewis, & Milo, 2010; Gonzalez-Esquer, Shubitowski, & Kerfeld, 2015.
		Plant	Production of novel substance or increased content of existing substance	Nutraceuticals such as carotenoid; Increased content of lignocellulose, oil, soluble sugar as bioenergy.	Laboratory	Fraser, Enfissi, & Bramley, 2009; Shih, Liang, & Loqué, 2016.
		Plant	Reduced need for inputs into agriculture	Engineered crops with reduced demands for inputs such as pesticide, water and nitrogen.	Laboratory	Abbas, Zafar, Khan, & Mukhtar, 2013; Park et al., 2015; Rogers & Oldroyd, 2014.
		Plant	New ways of self-incompatible crop breeding	Diploid potato breeding.	Laboratory, trial	Ye et al. (2018).
		Microbe	Biofertilizer or biopesticide production	Provide biofertilizer or biopesticide through plant-microbe interaction.	Laboratory, trial	Farrar, Bryant, & Cope-Selby, 2014; Project Auxin from iGEM (http://2011.igem.org/Team:Imperial_College_London).
	Pest/crop disease control	Microbe	Biosensors	Pathogen detection in plants and soil.	Laboratory	Damiati, Mhanna, Kodzius, & Ehmoser, 2018; Ostrov et al., 2017; Van Der Meer & Belkin, 2010.
		Microbe	Bio-insecticides	Fusion protein toxic to certain insects.	Laboratory	Abbas et al. (2013).
		Microbe	Synthetic microbe killing specific pests	Synthetic virus/fungus targeting and killing specific pests	Envisioned	Inceoglu et al. (2001).
		Insect	Sterile pests with synthetic gene drive system	Synthetic gene drive for sex-ratio distortion of certain pest group	Laboratory, trial	McFarlane, Whitelaw, and Lillico (2017).
	Environmental enhancement	Microbe	Biosensors	Pollutant test such as heavy metal.	Laboratory, trial, commercial	Joshi, Wang, Montgomery, Elfick, & French, 2009; Kim, Jeong, & Lee, 2018.
		Microbe	Bioremediation	Bioremediation of metal, radionuclides and other substances.	Laboratory, trial	Marques, 2018; Tay, Nguyen, & Joshi, 2017.
		Microbe	Tackling soil erosion	Engineered bacteria for promoting root growth and protecting the soil from erosion.	Laboratory, trial	Project Auxin from iGEM (http://2011.igem.org/Team:Imperial_College_London).
		Microbe	Biofuels	Production of cellulosic ethanol, diesel, etc.	Laboratory, trial, commercial	Mascoma (http://www.mascoma.com); Solazyme (http://solazyme.com).
	Livestock management	Microbe	Biosensor and biotherapeutics	Whole cell-mediated health monitoring and disease treatment	Laboratory	Krishnamurthy, Moore, Rajamani, & Panchal, 2016; Slomovic, Pardee, & Collins, 2015; Sola-Oladokun, Culligan, & Sleator, 2017.
		Microbe	Function of facilitating feed processing	Engineered microbe or enzyme for feed processing.	Laboratory, trial, commercial	Mascoma (http://www.mascoma.com); Metabolic Explorer SA (https://www.metabolic-explorer.com).
		Animals	Animal breeding	Breeding of new lines depending on synthetic gene drive, genome editing, synthesised genes, etc.	Envisioned	Gonen et al., 2017; Bhat et al., 2017.
Food	Food products	Microbe, plant	Novel foods	Casein for milk production from yeast; Egg white from yeast.	Laboratory, trial, commercial	Perfect Day (http://www.perfectdayfoods.com); Clara Foods (https://www.clarafoods.com).
		Microbe, plant	Food additives	Colorant and flavours (vanillin, raspberry ketone, Stevia et al.); nutraceuticals (vitamins, carotenoid et al.).	Laboratory, trial, commercial	Evolva (https://www.evolva.com); Hanson et al., 2018; Leonard et al., 2010; Nigam & Luke, 2016; Prima et al., 2017; Wang, Zada, Wei, & Kim, 2017.
	Food processing	Microbe	Improved fermentation process	Higher fermentation efficiency or better flavour products.	Laboratory, trial, commercial	Jagtap, Jadhav, Bapat, & Pretorius, 2017; Lee, Lloyd, Pretorius, & Borneman, 2016; Mays & Nair, 2018; iGEM Munich Team (http://synbio.info/display/synbio/Beer + with + caffeine).
	Food safety diagnosis	Microbe	Biosensors	Food toxin, pathogen, parasite or other substance detection.	Laboratory, trial	Sample6 (https://www.sample6.com); De Mora et al., 2011; Webb et al., 2016.
	Food waste processing	Microbe	Waste degradation and useful substance extraction	Engineered microbe for phosphorus recovery from food waste.	Laboratory, trial	Lakhundi, 2012; Tarayre et al., 2016.
	Food packaging	Microbe	Material production	Biodegradable material such as biopolymer.	Laboratory, trial, commercial	Jung, Kim, Park, & Lee, 2010; Yield10 Bioscience (https://www.yield10bio.com); Bioamber (https://www.bio-amber.com); GC Innovation America (https://www.gcinnovationamerica.com).

simultaneously increase the risks of releasing synthetic biological agents into the environment (Polizzi, Stanbrough, & Heap, 2018). A serious challenge for scientists and policy-makers can relate to risk assessment and governance, as the complexity of synthetic biology-based applications constantly grows, including those within the agri-food sector (Pauwels et al., 2013). In addition, the "bottom-up" approach of synthetic biology, which aims to create artificial or semi-artificial life *de novo*, has evoked strong ethical controversy (Bedau, Parke, Tangen, & Hantsche-Tangen, 2009). Thus, it is important to investigate public perceptions of and attitudes towards synthetic biology separately rather than intermingle the two technologies.

At present, around 700 organizations are engaged in synthetic biology-related research across 40 countries; and more than 350 companies have been established, which apply synthetic biology as part of their activities. The global market value of these companies was estimated to be $3.9 billion in 2016 (Bueso & Tangney, 2017). A number of applications have been developed for use within the agrifood sector (Table 1). However, future commercialisation of these applications could be uncertain due to societal concerns about potential risks and ethical issues (Polizzi et al., 2018). Companies which align their products with consumer preferences and priorities may gain commercial success (Raley, Ragona, Sijtsema, Fischer, & Frewer, 2016). In this context, the present study attempts to review the existing literature for understanding public perceptions and attitudes regarding synthetic biology, including those linked to agrifood applications. In addition, we attempt to compare the results with research on other emerging technologies, such as GM and nanotechnology, to identify differences and similarities in public perceptions and attitudes, and to assess whether it is possible to learn how best to commercialise applications of synthetic biology from other enabling technologies in the agrifood sector (see Frewer et al., 2011).

This paper therefore aims to address the following questions:

- Are there specific issues raised that distinguish synthetic biology from other enabling agri-technologies regarding public concerns?
- What factors may potentially affect the public's perceptions of, and attitudes towards, synthetic biology and its applications?
- What applications might the public and/or consumers prefer to be developed and commercialised within the agrifood sector?

This information will provide knowledge of direct relevance to those with interests in applying synthetic biology in the agrifood sector, in particular in relation to *which* applications can be developed, *how* products should be designed, and *how* governance can be optimised in the light of public and environmental health as well as societal preferences (Frewer et al., 2011).

2. Methodology

This paper applied a mapping review methodology to answer the proposed research questions by analysing and integrating existing research findings, and simultaneously identify current knowledge gaps (Grant & Booth, 2009). The relevant literature was identified using a two-stage search strategy between 1st July and 30th October 2018. In the first stage, 3 databases (Scopus, Web of Science and ProQuest) were searched to retrieve literature published between January 2004 and December 2018. The terms, (a) "synthetic biology"; (b) "attitude"; (c) "perception"; (c) "media coverage"; and (d) "press coverage" were used, in which (a) was separately combined with the other keywords. The returned references were screened and literature that was technical (i.e. which discussed the process and application of synthetic biology as a scientific process), unempirical, in languages other than English, or "misunderstood" the concept of synthetic biology (for example, equating it with GM) was excluded. In the second stage, additional references were obtained from the reference list of eligible studies identified in the first stage. A total of 24 studies were included, of which 8 were focused on analysis of media reportage of synthetic biology, and 16 were empirically-based public attitudes related research. A comparison of the retrieved studies was conducted, which focused on their methods used and research findings to address the proposed research questions.

3. Benefits, risks and ethical issues of synthetic biology-based agrifood applications

There is evidence to suggest that emerging technologies have the potential to establish new industries or transform existing ones, delivering both benefits and risks (e.g. human health, environmental and socio-economic impacts) (Myers, 2007). These all need to be considered during their development and implementation processes and integrated into the regulatory framework for technological governance. Previous studies have shown that benefit and risk *perceptions and attitudes* drive societal acceptance of innovative food technologies, such as GM (Frewer et al., 2013) and nanotechnology (Giles, Kuznesof, Clark, Hubbard, & Frewer, 2015). Specifically, different trade-offs between perceived potential risks, benefits and other issues are made during people's decision-making of such technologies (Bearth & Siegrist, 2016; Hu, Hünnemeyer, Veeman, Adamowicz, & Srivastava, 2004; Mather et al., 2012), and this may extend to synthetic biology (Akin et al., 2017; Pauwels, 2013).

The technical advances (for example, new/cheaper ways of DNA synthesis and tools for DNA assembly) and more open sourcing (for example, circulation of foundational tools and reusable synthetic parts) of synthetic biology have facilitated development of applications in different sectors, such as healthcare, energy, environment and agrifood. It is anticipated that these applications can provide new and cost-effective ways of disease treatment, drug and clean energy production, waste recycling, environment enhancement, among many others (Polizzi et al., 2018). Within the agrifood sector, synthetic biology offers better ways to improve crops, control pests and crop diseases, enhance the environment and manage livestock. It also has the potential to deliver advantages to novel food and food ingredient production, food processing, food safety diagnosis, food waste processing and food packaging development (Table 1).

Despite the potential benefits, multiple risk issues have also been raised in relation to human health, environmental, socioeconomic, and ethical impacts of synthetic biology. It is sometimes difficult to make precise risk calculations as the occurrence and consequences of a risk are associated with uncertainty (Rosa, 1998). This may indeed be the case for synthetic biology applied in the agrifood sector. For example, novel foods or food ingredients derived from synthetic organisms may be linked to public concerns about the uncertainties associated with their long-term impacts on human health, including increased allergenicity, as has been the case with GM and other novel foods (van Putten et al., 2006). The release of synthetic microbes or plants may have adverse environmental impacts through affecting other natural species, and subsequently cause negative impacts on human health after entering the food system (Polizzi et al., 2018). An example is the use of a synthetic gene-drive system to distort the sex-ratio of target pests, thereby reducing their ability to reproduce. Given the possibility of this system irreversibly entering other species, and the choice of insects as hosts, the application could be highly uncontrollable once released to the environment and subsequently damage the ecosystem more generally (Oye et al., 2014). In addition, upgraded techniques and open source platforms of synthetic biology make it easier to establish biological agents by people within or outside research institutes. It increases the possibility of intended (e.g. "bioterror") and unintended (i.e. "bioerror") release of dangerous biological agents (Polizzi et al., 2018), and may in turn affect the perceived and actual potential for adverse effects on human health and the environment.

Socioeconomic risks in relation to synthetic biology could also occur. For example, novel applications may negatively impact existing

Table 2
Analysis of media portrayal about synthetic biology.

Origins of reportage	Search method	Sample size	Period of media reportage	Data analysis	Research focus	Major findings	References
US and Europe	"Synthetic biology" was searched in major US newspapers based on *LexisNexis*; multilingual search for the term "synthetic biology" in major European newspapers (articles in English, French, Dutch, German, Spanish and Italian).	309 from US; 841 from Europe.	January 2003 to December 2011	Not reported	Change in the amount of coverage in relation to synthetic biology; key issues mentioned in media.	Coverage of synthetic biology in press grew in the 2008–2011 period when compared with the 2003–2008 period; A significant increase of coverage was seen in 2008 and 2010; energy and health applications were reported as benefits; the media reported concerns focused om biosafety, biosecurity and ethics.	Pauwels & Ifrim, 2008; Pauwels et al., 2012
Austria, Germany and Switzerland	Terms such as "synthetic biology", "artificial life", "designer AND organism", "minimal organism", "minimal genome", "bioengineer", "biomachine", "biobrick", "artificial DNA", "artificial proteins", "artemisinin", "biorobot", "synthetic bacterium", "synthetic virus" and "DNA AND synthesis" (German equivalents) were used to search the media database *APAdefacto* and *Google Alerts*.	233 in German	January 2004 to December 2009	Qualitative and quantitative content analysis	Synthetic biology topics covered by media coverage; framing of synthetic biology; related risks, benefits and applications.	Engineering metaphors are more prominent in media coverage; a new aspect of "playful description" of synthetic biology was identified in coverage compared with GM; ambiguities exist between the description of synthetic biology and GM.	Gaskell, Bauer, Durant, & Allum, 1999
English and German speaking countries	*GBI-Genios* database was searched using the term "Synthetische Biologie"; *LexisNexis* database was searched using "synthetic biology".	10831 in English; 1036 in German.	January 2004 to December 2015	Qualitative and quantitative content analysis	Framing of, and metaphors for, synthetic biology discussed in the media discourse.	A substantially higher frequency of engineering and IT related metaphors were identified in media coverage compared to religio-cultural expressions, such as "playing God" or "creating life".	Braun et al. (2018)
US	News articles were collected from *The New York Times* using the term "synthetic biology".	32	January 2005 to July 2015	Qualitative and quantitative content analysis	Framing of synthetic biology in the media; relationship between low reporting volume and public knowledge of synthetic biology along with the high level ethical, moral and political implications.	Ambiguity about potential ethical issues and the relation between synthetic biology and genetic engineering were identified, which might act as a barrier public engagement.	Giordano and Chung (2018)
Denmark, Finland, Norway and Sweden	Terms such as "Artemisinin", "artificial life", "synthetic life", "bio-brick", "bioterrorism", "DNA synthesis", "iGEM", "synthetic biology", *inter alia* (equivalents in four national languages) as well as names of renowned scientists were used for searching in newspapers' archives and through the media databases *Mediearkivet*, *Infomedia*, and *PressText*.	146	January 2009 to December 2014	Qualitative and quantitative content analysis	The tone of the articles analysed was assessed by the authors according to their interpretation of the narrative provided by the story; other issues assessed included the synthetic biology topics covered by media coverage; framing of synthetic biology; metaphors used for synthetic biology.	Potential benefits of synthetic biology were highlighted; the media portrayal of synthetic biology tended to be very positive; minor risks were mentioned mainly related to bioterror and bioerror; public involvement was rarely suggested as relevant.	Ancillotti et al. (2017)
Sweden and Italy	Terms such as "Artemisinin", "artificial life", "synthetic life", "bio-brick", "bioterrorism", "DNA synthesis", "iGEM", "synthetic biology", *inter alia* (Swedish and Italian equivalents) as well as names of renowned scientists were used for searching in newspapers' archives and through the media databases *Mediearkivet* and *PressText*.	131	January 2009 to December 2013	Qualitative and quantitative content analysis	The tone of the articles analysed was assessed by the authors according to their interpretation of the narrative provided by the story; other issues assessed included the synthetic biology topics of media coverage; framing of synthetic biology; metaphors used for synthetic biology; issues related to technology oversight or public interest or public engagement.	The portrayal was very positive, describing synthetic biology as a "biotechnology with great benefits and minor risks"; risks were mainly related to bioterror and bioerror; coverage of synthetic biology was more "event-driven", i.e. linked to novel developments etc. rather than about the technology *per se*; public involvement was rarely suggested as relevant.	Ancillotti and Eriksson (2015)

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Table 2 (*continued*)

Origins of reportage	Search method	Sample size	Period of media reportage	Data analysis	Research focus	Major findings	References
Netherlands	Terms such as "synthetic biology", "synthetic cell", "synthetic genome", "minimal genome", "iGEM", *inter alia* (Dutch equivalents) were used to search for newspaper articles in *LexisNexis* database.	261	January 2000 to November 2016	Qualitative and quantitative content analysis	The tone of the articles analysed was assessed by the authors according to their interpretation of the narrative provided by the story; other issues analysed included the synthetic biology; topics of media coverage; applications, risks, and ethical issues; and the use of metaphors in articles.	Dutch newspapers paid limited attention to synthetic biology; when it occurred, the coverage was more event-driven; The Dutch press tended to be neutral or positive about synthetic biology; healthcare and environmental applications were discussed in terms of potential benefits rather than in terms of risk and ethical issues; engineering related metaphors were more frequently used which potentially suggested that the technology is "controllable".	Borgers (2017)

supply chains, within which some stakeholders might suffer from negative economic consequences. The antimalarial drug (artemisinin) production by synthetic yeast may help stabilize the drug supply and decrease the cost, but traditional producers growing *Artemisia annua* for artemisinin extraction could be put out of business (Polizzi et al., 2018). In addition, the unbalanced adoption of synthetic biology-based agri-food applications, such as excessive growth of energy crops, may pose threats to food security if competition with food crops results (Harvey & Pilgrim, 2011). Ethical issues have also been frequently studied by ethics experts, in particular the raised concern about "playing God" or "tampering with nature" (Rogers, 2011). The potential for secondary use or misuse, together with other issues such as bioerror, bioterror, patent management, benefit distribution, research integrity, and regulations, has also been identified as containing potentially negative consequences (Newson, 2015; Rogers, 2011).

4. Media portrayal of synthetic biology

In contrast to technical assessment of risks and benefits, public responses to emerging technologies may be highly context-dependent, for instance, influenced by risk framing and market interaction (Falk & Szech, 2013; Kahneman & Tversky, 2000). Kasperson et al. (1988) suggested that social context, such as the information transfer system and response mechanisms of society, could lead to the amplification or attenuation of risk, and in turn impact behavioural responses. GM foods, for example, were presented as hazardous in a crisis context by the British media, which subsequently "amplified" or increased peoples' risk perceptions and negative attitudes (Frewer, Miles, & Marsh, 2002). The way in which synthetic biology is portrayed in the media may also affect public attitudes, in particular given that people know little about it at present (Kinder & Robbins, 2018; Oliver, 2018).

Table 2 identifies empirical studies that have analysed media portrayals of synthetic biology between 2003 and 2016 in North America and Europe. They have employed qualitative and quantitative content analysis to investigate themes, metaphors and tones of the media reportage. A substantial increase of synthetic biology-related coverage was seen in particular in 2008 and 2010 (Ancillotti, Holmberg, Lindfelt, & Eriksson, 2017; Pauwels & Ifrim, 2008; Pauwels, Lovell, & Rouge, 2012). The focus of the increased reportage was more associated with prominent events rather than potential risks and benefits of synthetic biology, mainly underpinned by events related to elite scientists' visions (J. Craig Venter Institute, 2008) and significant technical advance (Gibson et al., 2010). With respect to the identified coverage concerns, American and European media mainly presented bioerror, bioterror and ethical issues, of which ethical concern was a greater focus in Europe, and bioerror in America (Pauwels et al., 2012). Benefits of potential applications in healthcare, energy and environmental sectors were also introduced. Overall, media coverages describing only benefits, or balanced benefits and risks, outnumbered those predominantly underlining risks and/or ethical issues in both Europe and America (Ancillotti et al., 2017; Pauwels et al., 2012; Pauwels & Ifrim, 2008).

Metaphors applied in synthetic biology related coverage also have been studied. The results showed that the frequency of "religious" metaphors, such as "playing God" and "creating life", is substantially lower than engineering and information technology related metaphors (Ancillotti & Eriksson, 2015; Ancillotti et al., 2017; Borgers, 2017; Braun, Fernau, & Dabrock, 2018). Hellsten and Nerlich (2011) argued that engineering-related metaphors might suggest the controllability of applications, and potentially reduce readers' perceived risks. In addition, tone of published stories in the European media was categorised according to their normative impression (Ancillotti & Eriksson, 2015; Ancillotti et al., 2017; Borgers, 2017). For example, media reportage highlighting benefits or with an overall "approving" tone was assigned as "positive", and media coverage objectively introducing benefits and risks without value judgement was regarded as "neutral". Media reportage that portrayed synthetic biology as a negative development

Table 3
Literature focused on public perceptions of, and attitudes towards, synthetic biology.

Research method	Data analysis	Participants	Sample size	Demographic differences assessed	Information provided to participants	Participants' perceptions and attitudes	References
Observation on stakeholder discussion	Discourse analysis	Prospective politicians and synthetic biologists from Netherlands	Not reported	Not assessed	General introduction about synthetic biology and the current academic discussion. Information about specific applications was not presented.	The issues discussed focused on the need for synthetic biology and participant concerns about deliberate release, moral boundaries and political control.	Rerimassie (2016)
Focus group	Thematic analysis	Dutch citizens	46 (8 groups)	Not assessed	Although both a general introduction and applications (in relation to health, environment and food) were provided, the paper analysed participants' opinions about the technology *per se* and its development rather than upon different applications.	Participants discussed concerns about human health effects, the uncontrollability of applications, and ethical issues, although the results indicate that people are not inherently against or for synthetic biology.	Betten et al. (2018)
Citizen panel	Content analysis; frame analysis	Austrian citizens	67 (8 panels)	Not assessed	A general introduction and examples of applications were presented to participants (including synthetic yeast-based artemisinin, a modified organism for pest control, and synthetic algae-based biofuel) were provided to participants for discussion.	The anti-malaria drug production presented invoked concerns about potential long-term health effects and potential for bioerror, but the application was still assessed as "acceptable" to study participants. However, participants tended to oppose the use of synthetic organisms for pest control due to perceived uncontrollability, potential for long-term impacts and potential for bioterror; some participants expressed distrust in scientists, industries and authorities; "playing God" and unnaturalness were not mentioned by participants.	Steurer (2015)
Focus group	Descriptive and inferential statistics	Austrian citizens	49 (8 groups)	Not assessed	A general introduction about synthetic biology developed from the available media coverage was provided without discussion of specific applications.	Concerns were mainly focused on bioterror and potential environmental and health impacts; participants expressed skepticism about manipulating human and animal cells; values related to a group's identity may collectively affect their examination of technologies such as synthetic biology.	Kronberger et al. (2012)
Interview	Thematic analysis	Stable patients in German-speaking part of Switzerland	36	Not assessed	A general introduction and information about specific applications (engineered autologous cells for disease treatment) were provided.	Participants expressed concerns about "playing God" before being provided with information about specific applications; their attitudes became more positive after learning about specific applications.	Rakic et al. (2017)
Observation on stakeholder discussion	Not reported	Non-synthetic biologists in disciplines (e.g. social sciences, philosophy and biology) mainly from Europe	23	Not assessed	The paper does not report on whether any information has been provided to participants, and there is no presentation of about specific applications.	Participants (stakeholders) exhibited unrealistic expectations of what synthetic biology can deliver, at the same time expressing fears about the potential for bioterror; participants' attitudes depend on their values and interests, in line with their interests.	Verseux et al. (2016)
Observation on stakeholder discussion	Not reported	Scientists, members of NGOs, funding agencies, and industry mainly in Europe and America	124	Not assessed	A general introduction to synthetic biology was provided without discussion of specific applications.	"The creation of life" was expressed as a concern by the participants; participants were also concerned about potential threats associated with biohackers who conduct biological experiments individually or in small organizations.	Schmidt et al. (2008)
Focus group	Grounded theory	German and Austrian citizens	69 (9 groups)	Age had no effects on the discussions about synthetic biology; groups with higher educational level focused more	A general introduction to synthetic biology was presented, together with information about specific applications	Synthetic organisms intended for medical production are considered to be more beneficial and necessary than those	Starkbaum et al. (2015)

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Table 3 (*continued*)

Research method	Data analysis	Participants	Sample size	Demographic differences assessed	Information provided to participants	Participants' perceptions and attitudes	References
				on the benefits and regulation of synthetic biology compared to those with lower educational level.	(including synthetic yeast-based artemisinin, a modified organism for pest control and synthetic algae-based biofuel).	developed for pest control and energy; participants are more concerned about bioerror than bioterror; in relation to ethical concerns, equitable benefit distribution across different beneficiary was the issue most discussed.	
Survey and focus group afterwards	Descriptive statistics for survey data; not reported for focus group data	American citizens	3004 surveys and 8 focus groups	Not assessed	A general introduction to synthetic biology was presented, together with information about specific applications (including a synthetic virus for vaccine production, synthetic yeast-based artemisinin and altered pigs and cows with accelerated growth).	Medical and biofuel applications were accepted by most participants; applications which facilitated animal growth were less acceptable to participants than medical production using animals; potential long-term effects on human health and environment were a focus of concern.	Pauwels (2013)
Survey	Descriptive and inferential statistics	American citizens	1500	An analysis of demographic differences indicated that American males or those having higher income had lower risk perceptions regarding synthetic biology; no significant attitudinal differences were associated with education level or income.	A general introduction to synthetic biology was provided, but no information about specific applications was included.	Over 80% respondents reported knowing little about synthetic biology; the majority of participants perceived benefits to be more relevant than risks; people's risk perceptions were, however, associated with their cultural dispositions.	Mandel et al. (2008)
Survey	Descriptive statistics	American citizens	804	An analysis of demographic differences indicated that American males, participants with higher incomes or those with higher educational level tended to be more supportive of synthetic biology.	A general introduction to synthetic biology was provided, together with information about specific applications (altered mosquito for disease control, and a synthetic microbe for facilitating crop growth or food additive production).	People trusted scientists more than industry and government; concerns were expressed about the enabling technology in relation to its potential capacity to create harmful things, the "creation of artificial life" and potential for adverse human health effects; medical applications were more acceptable to participants than agrifood applications.	Hart Research Associates (2013)
Survey	Descriptive and inferential statistics	Canadian citizens	1201	Not assessed	A general introduction to synthetic biology was provided, together with information about a specific application (synthetic yeast-based food additive).	Perceived unnaturalness reduced people's acceptance of sweetener production using synthetic yeast.	Dragojlovic and Einsiedel (2013)
Survey	Descriptive and inferential statistics	People from 32 European countries	15,588	Not assessed	A general introduction to synthetic biology was provided, but no information about specific applications was included.	Most participants' attitudes towards synthetic biology tended to be supportive or neutral; belief in God is associated with participants' opposition to synthetic biology.	Dragojlovic and Einsiedel (2012)
Survey	Descriptive and inferential statistics	University students in Switzerland	1474	Female students perceived higher risks to be associated with synthetic biology and its applications; students in the humanities and social sciences perceived higher risks and lower benefits to be associated with synthetic biology than those in natural sciences.	A general introduction to synthetic biology was provided, together with information about specific applications (a synthetic microbe for pollutant sensing, and land bioremediation).	Participants showed more support for medical and environmental applications of synthetic biology than for GM crops; synthetic biology as an enabling technology is more accepted than GM, but less than nanotechnology.	Ineichen et al. (2017)
Survey	Descriptive and inferential statistics	American citizens	1771	Participants with higher educational level are supportive of synthetic biology; no significant attitudinal difference was found in terms of gender, income and age.	A general introduction to synthetic biology was provided, but no information about specific applications was included.	A range of factors influence people's attitudes towards synthetic biology. These include risk perceptions (reduced acceptance), benefit perceptions (increased acceptance), higher trust in scientists (increased acceptance), deference to science (increased acceptance), educational level (increased	Akin et al. (2017)

(*continued on next page*)

Table 3 (*continued*)

Research method	Data analysis	Participants	Sample size	Demographic differences assessed	Information provided to participants	Participants' perceptions and attitudes	References
						acceptance) and greater religiosity (reduced acceptance).	
Survey	Descriptive and inferential statistics	Indonesian students majoring in life science	50	Not assessed	A general introduction to synthetic biology was provided, which also addressed its potential for protecting biodiversity and developing healthcare products. However, no specific applications were presented.	Participants perceived both benefits and risks to be associated with synthetic biology; participants' attitudes varied between different applications; in particular respondents showed optimism about potential applications of synthetic biology in biodiversity conservation.	Kemal (2018)K

associated with negative implications was labelled as "negative". The findings indicated that the percentage of neutral or/and positive coverage was much higher than negative coverage in European media (Ancillotti & Eriksson, 2015; Ancillotti et al., 2017; Borgers, 2017).

Thus, the current media reportage about synthetic biology appears not to have negatively portrayed the technology in a manner that may amplify public risk perceptions or foster their negative attitudes. The relatively positive introduction of healthcare and energy applications by the media may possibly trigger public interest in synthetic biology. However, several issues associated with media coverage still need to be considered. For example, synthetic biology may have been "over-promoted" in terms of what it can potentially deliver, at least in the short term. This might decrease public trust in synthetic biology and associated research programmes, impeding its future development (Ancillotti, Rerimassie, Seitz, & Steurer, 2016). Verseux, Acevedo-Rocha, Chizzolini, and Rothschild (2016) have attributed the "hype" and presentation of far-future scenarios in the media to the lack of understandable documents about the current state of technological development for non-biologists. Another issue relates to the demand for clarity in defining and framing synthetic biology, which, once met, may facilitate public engagement and risk communication (Ancillotti et al., 2017; Giordano & Chung, 2018). As a result, better communication between academia and the media community is required to help develop clearer framing of synthetic biology and conduct effective science communication to the public in the light of specific applications and their current state of development.

5. Public perceptions of and attitudes towards synthetic biology *per se*

Research on public responses to synthetic biology has been relatively infrequent and mainly conducted in Europe and America (see Table 3). Participants often made sense of synthetic biology by comparing it with GM technology, while, for example, nanotechnology was less frequently mentioned as a "comparator" technology in public perception and attitude research (Kronberger, Holtz, Kerbe, Strasser, & Wagner, 2009; Kronberger, Holtz, & Wagner, 2012). Despite the ambiguous information about synthetic biology presented to research participants, another potential explanation is that the two technologies may be both perceieved to involve deliberate changes to cells at the genetic level. Consequently, public concerns about synthetic biology were expressed in a similar way to those associated with GM, although synthetic biology sometimes was perceived more negatively as people regarded it as a technological "upgrade" of GM (Steurer, 2015). In existing studies, people are mainly concerned about potential risks (e.g. potential environmental and human health impacts), moral, emotional or value-related issues (e.g. "unnaturalness", "creating life" and "playing God") and increased control of technology and patents by large companies (Betten, Broerse, & Kupper, 2018; Hart Research Associates, 2013; Mandel, Braman, & Kahan, 2008). The public distrust of major stakeholder groups (e.g. scientists, industry and government) was also identified in research (Betten et al., 2018). However, research participants expressed more optimism when applications benefiting human health, energy and environment were presented to them (Betten et al., 2018; Pauwels, 2009).

Individual attitudes towards synthetic biology were not only associated with their risk and benefit perceptions, but also "value predispositions" (e.g. religiosity and deference towards scientific authority) and trust in scientists (Akin et al., 2017). Deference towards scientific authority represents the long-term and stable belief that scientific enterprise focuses on the best interests of the public, which is correlated with individual's support for other technologies, such as nanotechnology (Anderson, Scheufele, Brossard, & Corley, 2012). Trust in scientists has been defined as the short-term and individual confidence in scientists' motivation and competency (Akin et al., 2017). Dragojlovic and Einsiedel (2012) reported that more religious respondents are less supportive of synthetic biology. However, the influence of religiosity on people's attitudes decreases when they have higher confidence in the institution of science. Among those less deferential towards scientific authority, higher-level trust in scientists could positively affect support for synthetic biology (Akin et al., 2017).

The association between public attitudes towards synthetic biology and their demographic characteristics, such as gender and educational background, was also studied (see Table 3). Men in the US perceived lower risks associated with synthetic biology in comparison to women (Mandel et al., 2008), a demographic difference also reported for other technologies (Finucane, Slovic, Mertz, Flynn, & Satterfield, 2000). Finucane et al. (2000) attributed the "white male effect" to men's perceiving themselves to be more involved in controlling and benefiting from technologies than women in the US. People with higher educational level were reported as exhibiting a tendency to be more supportive of synthetic biology (Akin et al., 2017), as were students with natural science backgrounds, compared to those studying humanities and social sciences (Ineichen, Biller-Andorno, & Deplazes-Zemp, 2017). The influence of educational level and gender on public attitudes, however, was sometimes found insignificant in quantitative studies into synthetic biology, as is the case for what has been found in GM-related studies (Akin et al., 2017; Frewer, Howard, & Shepherd, 1996; Kahan, Braman, & Mandel, 2009; Verdurme & Viaene, 2003). There is evidence that gender differences in public attitudes to GM disappeared after the tangible benefits of specific GM foods have been presented to participants (Frewer et al., 1996). It again implicates the importance of contexts during assessment of attitudes, which may shape perceptions of benefit associated with specific products or applications.

6. Public perceptions of synthetic biology-based applications in the agrifood sector

Public attitudes often varied according to different applications of emerging technologies. A recent systematic review indicated that people held more positive attitudes towards GM plants and their derivative products compared to attitudes towards GM animal products (Frewer et al., 2013). GM animals were less accepted if they were modified for food use rather than for medical reasons, as medical applications were possibly perceived to be more "necessary" than those related to food (Frewer, Coles, Houdebine, & Kleter, 2014). In the case of nanotechnology, medical and environmentally beneficial applications tended to be viewed as more acceptable by consumers (Priest & Greenhalgh, 2011). Within the food domain, nanotechnology for developing food packaging is more likely to be supported than food products for consumption (Giles et al., 2015).

The pattern of results for synthetic biology applied in the agrifood sector is not greatly different to other technological applications, although differences in study design across technologies have made comparisons more complex. In the case of synthetic biology, more positive perceptions were found to result among research participants after concrete examples of applications were introduced (Ineichen et al., 2017; Rakic, Wienand, Shaw, Nast, & Elger, 2017). People expressed more optimism about medical applications, such as synthetic microbes used for the production of medicine (Ineichen et al., 2017; Pauwels, 2013; Starkbaum, Braun, & Dabrock, 2015; Steurer, 2015), and disease treatment using engineered autologous cells (Rakic et al., 2017). However, concerns about the unknown long-term impacts of such medicines on human health, unintended release of synthetic microbes, and economic interests were still raised. Also, environmental applications were more acceptable to participants than agricultural applications. Although released synthetic microbes are more uncontrollable regarding their reproduction and spread, participants still showed more support for those applied in pollutant sensing and bioremediation compared to GM maize (modified to faciliate reduced application of herbicides/insecticides) and rice (modified to increase levels of pro-vitamin A) (Ineichen et al., 2017). As a result, synthetic biology-based applications for environmental enhancement (e.g. synthetic microbe as biosensors and for bioremediation) might be preferred by the public compared to those for crop improvement (e.g. productivity increase and reduced needs for inputs in agriculture) (see Table 1).

Generally, people tend to express more negative attitudes to synthetic biology applied in agricultural and food production (Pauwels, 2013; Steurer, 2015). Synthetic organisms (e.g. virus, bacterium and insect), developed either for pest control or boosting plant growth, posed concerns for research participants due to their uncontrollability, unknown long-term health impacts and their potential for bioterroristic use (Steurer, 2015). It is notable that mosquitos engineered by synthetic gene-drive systems for facilitating the eradication of malaria were perceived to be highly uncontrollable, but people did not express strong opposition to this application (Hart Research Associates, 2013), again suggesting that medical applications were perceived to be more "necessary" than agricultural applications (Starkbaum et al., 2015). Other agrifood applications, such as animals with accelerated growth and synthetic microbes applied to facilitate food production (e.g. production of food additive), were viewed more negatively by research participants (Hart Research Associates, 2013). This could potentially relate to consumers' concerns about their unknown long-term impacts as well as perceived unnaturalness of the food production process (Román, Sánchez-Siles, & Siegrist, 2017). A study by Dragojlovic and Einsiedel (2013) indicated the negative influence of perceived unnaturalness on participant acceptance of synthetic yeast-based sweetener, in particular among participants who regarded nature as sacred or spiritual.

The above evidence suggests that people's attitudes appear to vary by application types of synthetic biology, either across sectors or within the agrifood sector. Medical and environmental applications could be more acceptable than those applied in food and agricultural production. However, agrifood applications with tangible and desirable benefits may also be accepted, such as novel food products with health benefits (e.g. nutraceuticals), since they could evoke more positive perceptions compared with those delivering no health benefits. Application of synthetic biology for food packaging development may also be supported according to people's preferences for nanotechnology applications (Giles et al., 2015). So, of the listed agrifood applications in Table 1, the public may prefer those for environmental enhancement, producing healthy food products and food packaging to be developed and commercialised. These findings also imply that public perceptions and attitudes regarding synthetic biology are linked to attributes of specific applications, as is the case for GM and nanotechnology (Frewer et al., 2013; Giles et al., 2015).

7. Discussion

At present, there are no specific issues identified from existing research which distinguish synthetic biology from other enabling technologies, in terms of public perceptions and attitudes (Akin et al., 2017; Steurer, 2015). However, some issues uniquely associated with synthetic biology may need further consideration. For example, open-sourcing of synthetic biology improves accessibility of technology development to non-professionals, which may increase risks in relation to both bioterror and bioerror. When applied as a "bottom-up" approach, ethical aspects become more prominent in societal discussions (Bedau et al., 2009). Therefore, it is important to study the influence of these two issues on public attitudes and associated governance practices by linking them to specific applications and other contexts. In addition, as more novel applications are being developed, ambiguities in regulation may occur, and improvement of regulation and governance is therefore needed. Taking the arsenic biosensor (where synthetic bacteria contained in a secure casing) as an example, the developers' application for exemption from The Contained Use Directive (2009/41/EC)[1] and The Deliberate Release Directive (2001/18/EC)[2] was not approved in the European Union. This was because the application was technically "contained" but applied outside of a laboratory (European Food Safety Authority, 2015).

With respect to the public attitudes towards synthetic biology, social amplification of perceived risks does not seem to have arisen, as the media portrayal is, to date, relatively positive. There is also little evidence showing an "inherent societal aversion" to synthetic biology as an enabling technology (Betten et al., 2018; Pauwels, 2009). While a number of agrifood applications have been identified as potentially preferred by the public for development, there is still a lack of relevant studies to support this in practice, which makes it difficult to more accurately predict public priorities and preferences from Table 1.

A limited number of studies have identified factors that may affect public attitudes, such as perceptions of risks, benefits and ethical issues, trust in scientists, industry and government, and individuals' socioeconomic, demographic and value attributes. Although findings in relation to the influence of individual socioeconomic and demographic characteristics as reported in the literature is somewhat inconsistent, ongoing research that assesses how perceptions and attitudes in different demographic groups vary is required in order to develop more targeted risk communication strategies (Frewer et al., 2013). Integrating findings of research on synthetic biology as well as GM and nanotechnology, participants' perceptions and attitudes were linked to specific characteristics of applications, and they tended to hold more optimism after being informed of concrete benefits of applications. Metaphors such as "Playing God" and "creating life" were infrequently mentioned in the context of specific applications of synthetic biology, and perceived "unnaturalness" was only identified in food production (Dragojlovic & Einsiedel, 2013). These results suggest that, in common with other agri-technologies, risk and benefit perceptions may contribute in shaping public attitudes towards synthetic biology and its specific applications. Notably, these studies have tended to focus on synthetic biology *per se* rather than specific applications, and no research, so far, has investigated *how* trade-offs between benefits, risks and other issues are made by people during decision-making.

Previous research has shown that the benefits of GM technology perceived by research participants were often discounted (Siegrist & Sütterlin, 2016), and that risk and benefit perceptions of the same product can differ due to diverse personal characteristics (Hu et al., 2004). Individuals' trade-offs between perceived benefits, risks and other issues in decisions-making were also heterogeneous regarding the innovative food technology acceptance (Bearth & Siegrist, 2016). In other words, the role of different perceptions in determining public attitudes could be highly variable, and may be affected by various factors, such as the type of technology, socio-demographic, cultural or geographical differences between participants, and even regional differences in legislation of the studied food technology (Bearth & Siegrist, 2016; Costa-Font & Gil, 2009). The review also suggests that the public's actual responses/behaviour towards synthetic biology could be dependent on different contexts, such as the product type, media reportage, peer influence, risk framing and types of market interaction, rather than a rational cost and benefit assessment (Falk & Szech, 2013; Kahneman & Tversky, 2000; Oliver, 2018). Altogether, these differences highlight the need to consider a range of different factors that contribute to the context in which the technology is considered. Also, public perceptions and their influence on people's attitudes need to be investigated in the context of specific applications, in particular those with concrete and tangible benefits, so as to avoid unnecessary scares and encourage the acceptance of synthetic biology applied in the agrifood sector (Hansen, Holm, Frewer, Robinson, & Sandøe, 2003). Specifically, it is important to understand *how* people make trade-offs between their perceived benefits, risks and other issues of synthetic biology, together with contextual factors that may impact the decision-making process.

The process of reviewing the literature also highlighted some problems in experimental design. Some studies over-emphasised the origins of genes, which is a defining characteristic of GM, rather than the attribute of synthetic biology applications (Amin et al., 2013; Dragojlovic & Einsiedel, 2013). Fischer and Frewer (2009) argued that people's risk and benefit perceptions of unfamiliar foods are more dependent on the *ad hoc* affect or attitude shaped by the information initially presented, whilst prior attitudes may play a major role regarding foods that are familiar to people. In other words, if the presentation of synthetic biology to the public is framed primarily based on attributes of GM, people's attitudes towards synthetic biology-based applications could be biased due to their affect or prior attitudes relevant to GM products, in particular when people think these applications of synthetic biology are equivalent of GM products and are familiar to them. Furthermore, when developing experimental information interventions, the introduction of synthetic biology should be clear, and selected examples of application should be realistic rather than "blue sky ideas".

It is also notable that previous research on the factors that drive agrifood technology acceptance has tended to occur after societal rejection, delivering greater understanding of drivers of public rejection as opposed to acceptance (Frewer et al., 2014). In the case of synthetic biology, it is important to ensure societal and consumer engagement occurs throughout the research and development process. That is, as the technology evolves, a number of research questions need to be further answered prior to, and during, the commercialisation process associated with agrifood applications. These include:

- What are the public preferences for potential applications of synthetic biology in the agrifood sector? And what "features" or characteristics of products will align with societal preferences and priorities?
- What influences peoples' decisions about the acceptability or otherwise of specific applications of synthetic biology? Will factors such as "open sourcing" and perceptions that "life is being created" impact people's decisions?
- How can key stakeholders in synthetic biology development (including scientists, industries and policy makers) "fine tune" the development and commercialisation process in line with societal priorities and expectations? What information and knowledge need to be exchanged with societal stakeholders, and how might this be achieved?

8. Limitations of the research

At present, and as has been noted, there is limited literature available for review. Despite extrapolating from research into public attitudes towards GM and nanotechnology, the authors have been unable to further identify public priorities for development from the listed applications in Table 1. The lack of empirical research has also impeded comparisons of attitudinal differences across regions and time. As a consequence, important research gaps have been identified, which, once filled, will benefit the development of commercialisation trajectories for different agrifood applications, as well as the development of effective governance practices.

9. Conclusions

Synthetic biology has undergone considerable growth in recent years, with various potentially beneficial applications in the agrifood

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009L0041 (accessed 6 May 2009).

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32001L0018 (accessed 12 Marth 2001).

sector under development. However, the future commercialisation of these applications could be uncertain due to public risk perceptions and ethical concerns. Given the relatively positive media portrayal at the present, public attitudes appear to be uncrystallised. Also, people's attitudes and perceptions are likely to vary according to traits of applications. For instance, the public are inclined to accept applications for environmental enhancement, healthy food production and food packaging development. However, current studies into public attitudes towards synthetic biology have focused more on the technology *per se*, but have failed to contemplate application types, which has impeded further identification of public priorities from Table 1. This is also an important research gap which merits investigation, as it can guide "fine-tuning" characteristics of applications in particular those at critical development points and in turn optimise the commercialisation process. Other contextual factors, in particular those affecting the impacts of perceptions on people's acceptance or rejection of synthetic biology, should also be investigated. This information, together with the public priorities, could provide the basis for more effective public risk communication and regulatory mechanisms establishment, for example, in relation to identification and discussion of potential (socially prioritised) benefits in agrifood governance. In summary, better framing of synthetic biology needs to be developed for conducting relevant research and effective public engagement. More studies into public responses to synthetic biology are also required, which may provide information for "fine tuning" technical researchers' experiments, companies' product design and commercialisation, and forming the basis for more effective regulation mechanisms.

Declarations of interest

None.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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