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Bridging the gap between the science of cultured meat and public perceptions

A. Janet Tomiyama [a], N. Stephanie Kawecki [b,c], Daniel L. Rosenfeld [a], Jennifer A. Jay [d,e], Deepak Rajagopal [e], Amy C. Rowat [b,c,*]

[a] Department of Psychology, University of California, Los Angeles, 502 Portola Plaza, Los Angeles, CA, 90095, USA
[b] Department of Bioengineering, UCLA, 410 Westwood Plaza, Los Angeles, CA, 90095, USA
[c] Department of Integrative Biology & Physiology, UCLA, Terasaki Life Sciences Building, 610 Charles E. Young Drive South, Los Angeles, CA, 90095, USA
[d] Department of Civil & Environmental Engineering, Samueli School, UCLA, 520 Portola Plaza, Los Angeles, CA, 90095, USA
[e] Institute of the Environment & Sustainability, UCLA, LaKretz Hall, 619 Charles E Young Dr E, Los Angeles, CA, 90024, USA

A R T I C L E I N F O

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A B S T R A C T

Background: The environmental impact of meat consumption requires immediate action. Cultured meat—which is emerging through technologies to grow meat ex vivo—has exciting potential to offset the burden of livestock agriculture by providing an alternative method to sustainably produce meat without requiring individuals to become vegetarian. However, consumer uptake of cultured meat may be challenged by negative public perceptions.

Scope and approach: In this Review, we assert that the academic sector can play a vital role by understanding and communicating the science of cultured meat to the public. We discuss how crosstalk between the science and technology of cultured meat and the behavioral sciences will be critical to overcome challenges in public perceptions, and ultimately to realize the environmental benefits of cultured meat. We identify research and outreach priorities for the academic sector as well as potential policy actions to achieve the maximum benefits of cultured meat for planetary health.

Main

The heavy consumption of meat is a significant environmental burden that threatens the Earth's ability to sustain a projected population of 9 billion by 2050 (Steinfeld, 2006). More than 90% of the world's population eats meat (Halweil & Nierenberg, 2008, pp. 61–74). Getting the world's population to go vegetarian is simply not a feasible solution, because most humans love to eat meat (King, 2013) and eating behavior is difficult to change (Rosenfeld, 2018). Given these challenges, a possible solution is cultured meat,[1] which is an emerging technology that relies on cultivating meat from muscle cells ex vivo (Fig. 1A). Cultured meat has exciting potential to provide an alternative method for sustainable food production: a single muscle biopsy from one living cow could theoretically provide 1 billion beef burgers in 1.5 months whereas the equivalent number of burgers produced by conventional methods would require 0.5 million cows over 18 months (Food and Agriculture Organization of the United Nations, 1996; Hayflick, 1965). However, longstanding behavioral science has shown that people are skeptical and even fearful of new foods (Rozin & Vollmecke, 1986). Cultured meat products have yet to come to market and people have thus not yet had the opportunity to taste them or assess their price. However, there is sufficient evidence that consumers already have negative perceptions of cultured meat, which will likely challenge its uptake (Hartmann & Siegrist, 2017). In this Review, we highlight the

* Corresponding author. Department of Integrative Biology & Physiology, UCLA, Terasaki Life Sciences Building, 610 Charles E. Young Drive South, Los Angeles, CA, 90095, USA.
E-mail address: rowat@ucla.edu (A.C. Rowat).

[1] There are several terms used to describe this product, such as "cell-based meat," "lab-grown meat," "in vitro meat," "synthetic meat," and "clean meat" (Ong, Choudhury, & Naing, 2020). In this Review, we use the term "cultured meat" for the following reasons: 1) Technical terms such as in vitro meat and lab-grown meat can be alienating (Bryant & Barnett, 2019); 2) Conventional meat also consists of cells, so cell-based meat is not specific to cultured meat; 3) The terminology "clean meat" implies that conventional meat is not clean; 4) Culturing is a process that has long been used in food production (as in fermentation), which makes the term familiar while also capturing the process of culturing cells in vitro.

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negative, preconceived notions—or 'barriers'—to the uptake of cultured meat that are already shaping consumer attitudes, and may risk dominating food choices once cultured meat comes to market. We posit that proactive strategies are necessary to address these barriers prior to the emergence of cultured meat on the market; such strategies could include increasing the acceptability of cultured meat by using science and technology to improve cultured meat flavor, texture, and processes; advancing knowledge of public perceptions through research in behavioral sciences; transparently communicating scientific information about cultured meats; as well as implementing changes in policy. We structure this Review by presenting the anticipated environmental benefits of cultured meat, identifying barriers to the potential widespread consumption of cultured meat, and providing possible solutions to overcome those barriers.

Reducing livestock production will be critical for human and planetary health. Average annual global meat consumption is 44 kg per capita and is expected to rise in developed economies (Godfray et al., 2018). However, the mass production of livestock has numerous negative impacts on human and planetary health. Livestock production is the largest consumer of environmental resources in the food industry (Steinfeld, 2006) and contributes to 14.5% of global greenhouse gas (GHG) emissions (Gerber et al., 2013), 8% of freshwater use (Nardone, Ronchi, Lacetera, Ranieri, & Bernabucci, 2010), and 30% of land use (Steinfeld, 2006). The heavy use of antibiotics in animal agriculture also promotes antibiotic resistance; this major threat to public health is responsible for 2 million antibiotic resistant infections and over 23,000 deaths per year in the U.S. (Centers for Disease Control and Prevention, 2013). As Springmann and colleagues conclude, with increasing planetary temperatures, rising sea levels, more frequent droughts, and depleted water resources, the environmental pressures of food production have already surpassed sustainable limits (Springmann et al., 2018). Changes in food system practices will thus be critical to support the health of people and the planet. If meat-eaters in the U.S. alone were to reduce their consumption of mass-produced beef by just 20%, this would result in 100 million metric tonnes per year reduction in GHG emissions, which is nearly one third of the U.S. goal set in the Paris Climate Accord (Springmann et al., 2018).

However, eating behaviors are in general very difficult to change as evidenced by the high prevalence of diseases where overconsumption is a risk factor, such as cardiovascular disease (Benjamin et al., 2019) and type 2 diabetes (Cho et al., 2018; Dohle, Diel, & Hofmann, 2018; Mann et al., 2007). Controlling eating requires multiple aspects of self-regulation and executive function (Dohle et al., 2018), and often involves a battle against ingrained habits and environments that make controlling eating more difficult (Johnson, 2013; Wood, 2016). While a small fraction of people are motivated to become vegetarian for environmental, religious, health, or animal rights/welfare-related reasons (Rosenfeld, 2018), the majority of consumers do not change their meat-eating behaviors (Verbeke, Pérez-Cueto, de Barcellos, Krystallis, & Grunert, 2010). Informational strategies that raise awareness about environmental and health benefits of eating less meat have achieved only modest reductions in meat consumption (Morris, Kirwan, & Lally,

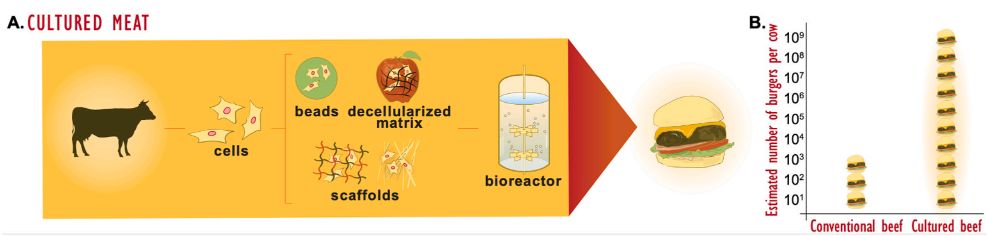


Fig. 1. A. Cultured meat can be generated from muscle stem cells that can be isolated from a living animal, which are cultivated in vitro. To support cell growth in a bioreactor, cells can be grown on beads made of naturally-derived polymers such as dextran or synthetic polymers such as polystyrene (Verbruggen et al., 2018). Shown here is a snapshot of strategies to produce cultured meat; other proof-of-concept processes can be used to culture cells on edible scaffolds (Ben-Arye et al., 2020; MacQueen et al., 2019; Modulevsky, Lefebvre, Haase, Al-Rekabi, & Pelling, 2014). One strategy to provide a substrate for cell growth is to use decellularized fruits or vegetables to harness the inherent porous structure of plants (Campuzano & Pelling, 2019). For example, the leaves of spinach have natural branching veinous structures that mimic the vasculature of muscle; by removing the plant cells using detergent or enzymes the resultant "decellularized" leaf provides a three-dimensional (3D) scaffold to which animal cells can adhere (Gershlak et al., 2017). Developing scaffolds of proteins or carbohydrates to mimic the structures of the extracellular matrix of muscle is another emerging approach using extrusion or polymer-spinning methods (MacQueen et al., 2019; Ozbolat & Hospodiuk, 2016). **B.** The estimated magnitude of scale of burgers that could be produced from one animal using cultured and conventional methods. Here we use burgers to illustrate the estimated number of cultured beef burgers that could be theoretically produced from one animal versus the average number of burgers that could be produced using conventional methods (Food and Agriculture Organization of the United Nations, 1996). Estimates are based on 113 g beef per burger.

2014). Cultured meat may be a promising solution because it allows consumers to continue eating meat while at the same time offsetting the environmental burdens of mass meat production (Mattick, Landis, Allenby, & Genovese, 2015).

Growing muscle from cells in vitro is a promising approach to reduce the environmental impact of meat. To culture muscle, precursor muscle stem cells are harvested from animals; the resultant differentiated myoblasts are expanded in culture, further differentiated into myotubes, and grown into skeletal muscle tissue, which is a primary component of meat (Verbruggen, Luining, van Essen, & Post, 2018) (Fig. 1, Box 1). To produce cultured meat on a large scale, cells can be cultivated in a bioreactor on the surface of inert beads; this provides myoblasts with a solid surface to which they can attach and maximizes surface area. Following proliferation, cells are harvested from the beads, and blended into a unified meat product (Bodiou, Moutsatsou, & Post, 2020).

The process of culturing meat would significantly reduce the number of livestock needed for food consumption. To give a sense of scale, our back of the envelope calculation indicates that ~1 billion cultured beef burgers (113 g each) could be produced in 1.5 months from muscle stem cells biopsied from one living cow given a Hayflick limit of more than 50 cell divisions (Hayflick, 1965); this is based on observations that immortalized mesenchymal stem cells can achieve > 50 divisions and that cells are equally proliferative across earlier and later cell divisions (Fang, Wei, Teng, Zhao, & Hua, 2018; Lucas et al., 1995). As noted above, the equivalent number of burgers produced by conventional methods would require 0.5 million cows over 18 months (Food and Agriculture Organization of the United Nations, 1996). While there may be additional energy requirements to culture meat, there could be dramatic reductions in land use and GHG emissions compared to conventional beef, as quantified by life cycle analysis (LCA) (Mattick et al., 2015; Pelletier, Pirog, & Rasmussen, 2010), which provides a systematic approach to quantify different types of material use (e.g. energy, water, land) and environmental releases (e.g. GHG, air and water pollutants) associated both directly and indirectly with a given unit of a specific product—such as a kilogram of beef (Rajagopal, Zapata, & Maclean, 2017).

Consumer adoption of cultured meat faces major barriers. Despite the potential environmental benefits of cultured meat, we assert that negative consumer perceptions will pose a major challenge for consumption. Cultured meat will not provide environmental benefit if no one eats it. Evolutionarily, humans are predisposed to distrust and dislike unfamiliar foods—a phenomenon known as food neophobia (Rozin & Vollmecke, 1986). Indeed, studies have observed considerable skepticism of cultured meat, even among highly educated consumers (Hocquette et al., 2015). We next discuss potential barriers to consumer uptake of cultured meat that we think are important to address (summarized in Fig. 2), and argue that resolving misconceptions requires an interdisciplinary approach that marries behavioral science to the technology of cultured meat. As will become evident, different barriers will require different approaches—some solved by science and technology, others by education, and still others by policy.

Barrier: Taste and Texture. Taste emerged as the leading concern for consumers in a survey about cultured meat conducted in the U.S. (Wilks & Phillips, 2017). Indeed, flavor and texture are critical factors that drive food choices (Mouritsen & Styrbæk, 2017). Technological advances can address this barrier. Current methods use beads as a substrate to grow cells as building blocks of cultured meat (Box 1); this can support blended products, such as burgers and hot dogs, whose flavor could be enhanced with approaches currently used in the food industry like adding emulsions to encapsulate fat or specific molecules to enhance flavor (Box 2). To achieve cultured meat that mimics the texture of different cuts of meat, muscle fibers can be produced on edible scaffolds generated using techniques from tissue engineering and regenerative medicine; some of these approaches are already used in plant-based meat (Box 2). Scaffolds with striated textures that mimic the inherent structure of muscle have been shown to promote myotube formation (Ostrovidov et al., 2014). While some scaffolds may be degraded and/or remodeled by cells, other scaffold materials may retain their structure and mechanical properties (Langelaan et al., 2010), which could thereby impact cultured meat texture. Recent progress has been made towards developing edible scaffolds for cultured meat production. Animal-derived source ingredients, such as gelatin—which derives from the from the extracellular matrix (ECM) protein collagen—provides a natural scaffolding material for muscle cells. A fibrous gelatin scaffold generated using immersion rotary jet spinning promotes the culture of bovine and rabbit-derived muscle cells, and formation of aligned muscle tissue (MacQueen et al., 2019). Scaffolds with aligned grooves have also been produced by micromolding thin hydrogel films (Orellana et al., 2020). Plant-based materials are also showing promise for scaffolds: textured soy protein, which has an inherently porous structure, has been shown to successfully support the growth of bovine myotubes (Ben-Arye et al., 2020). While plant-based scaffolds may require chemical functionalization or pre-treatment with an ECM protein to promote adhesion of animal cells, there may be energetic benefits to harnessing the porous structures of plants, fungi, or plant-based byproducts as scaffolds for cultured meats.

Cultured meat that mimics specific cuts of meat such as a beef steak, pork shoulder, or bacon, will require recreating spatially defined structures such as vasculature and intramuscular fat to improve flavor, texture, mouthfeel. Ultimately meat with spatial structure will require methods to pattern cells and/or composite scaffolds that can be tuned to preferentially support the growth of multiple cell types to replicate native meat structure. To enable spatial control over the deposition of scaffolds and multiple cell types, 3D printing is a promising approach to produce functional organs ex vivo (Lee et al., 2019); it remains to be determined what level of muscle functionality may be optimal for cultured meat taste and texture. While there are technological barriers in scaling up 3D printing methods to enable cost-effective production of cultured meats, there is active progress in this space (Portanguen, Tournayre, Sicard, Astruc, & Mirade, 2019).

Engineering vasculature into cultured meat is an important strategy to facilitate the growth of thicker "cuts" of cultured meat, which can be hindered by diffusion-limited exchange between cells and media. To estimate the maximum thickness of viable tissue that can be obtained by

Box 1
- Meat from cells to muscle.

The hierarchical structure of meat is illustrated from left to right. The process of generating cultured meat is depicted from right to left, with the ultimate goal to generate complex muscle structures that mimic meat, which include muscle fibers, connective tissue, fat, and vasculature. Steak is comprised of bundles of muscle fibers organized within connective tissue. Individual fibers result from the fusion of myotubes, which are multinucleated cells. Myotubes are the building blocks for cultured meat, and can be derived from muscle stem cells that are isolated from a living animal. To produce cultured meat requires differentiation of muscle stem cells into myotubes, which can be achieved by culturing them on a substrate (inert bead or scaffold as shown in Fig. 1). Myotubes can either be harvested from the substrate prior to processing into a cultured meat product. Ongoing efforts are focused on developing edible scaffolds.

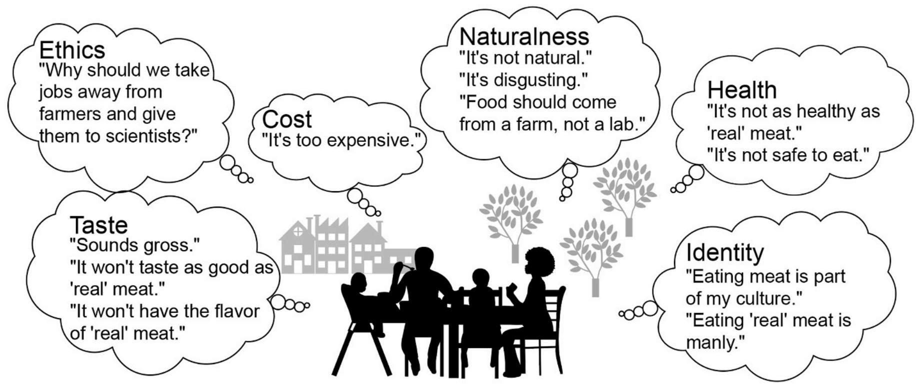


Fig. 2. Overview of common consumer perceptions posing barriers to the potential uptake of cultured meats.

Box 2
- A note about plant-based meats

This Review focuses on cultured meats, as the technology is still evolving and products have not yet come to market. By contrast, plant-based meat products have already gained popularity as evidenced by their availability across multiple continents and in American fast food chains like Burger King, Del Taco, and KFC. Plant-based meat products aim to emulate the taste, texture, and color of meat using ingredients sourced from plants, which are processed using approaches from science and engineering to tune texture and flavor. Emulsification is used to entrap fats or flavor molecules in droplets of an emulsion. Fibrous textures can be generated using extrusion to mold ingredients into fibers. Industrial fermentation is used to generate specific color and flavor molecules, such as heme-containing proteins, and can also be harnessed to generate source ingredients, such as collagen. While plant-based meat products aim to simulate meat texture and flavor, the extent to which these products fulfill consumer desire for meat remains to be fully understood.

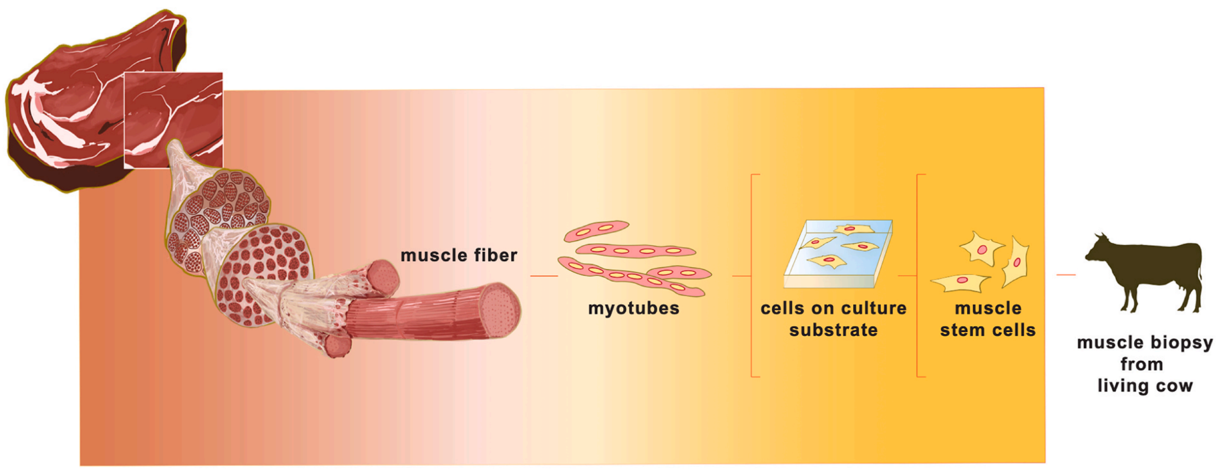
Despite the widespread prevalence of plant-based meats, different approaches will be needed to fully understand the barriers and potential solutions for adapting cultured meat as it faces different barriers (Bryant, Szedi, Parekh, Desphande, & Tse, 2019) and has different potential solutions. For example, men are less receptive to eating a plant-based diet (Rosenfeld, 2018) but are actually more receptive to eating cultured meat than women (Bryant & Barnett, 2018). But there are also similar challenges that may face plant-based and cultured meats. Plant-based meats contain ingredients to enhance texture and flavor, and there is a misperception that foods should be avoided when they contain multisyllabic ingredients (Pollan, 2009). Similar additive ingredients may be necessary for scaffolds to optimize the texture of cultured meats (Fig. 1) (Ben-Arye et al., 2020; MacQueen et al., 2019). Concerns of additive ingredients in both plant-based and cultured meat provide educational opportunities for scientists to communicate the importance of molecules in plants and animal physiology, and to distinguish the multisyllabic ingredients that originate from natural sources versus those that may have negative health consequences.

A separate issue is whether there will be room in the marketplace for cultured meats and plant-based meats. As evidenced by the popularity and penetration of plant-based meats into fast food restaurants, consumer acceptance is relatively high already for these products. One study of consumers across the UK, Spain, Brazil, and the Dominican Republic found that people were more willing to purchase plant-based meats than cultured meat or insect-based proteins (Gómez-Luciano, de Aguiar, Vriesekoop, & Urbano, 2019). In particular, those who are motivated by animal welfare and health concerns may prefer plant-based meats. However, there are also segments of the population, such as men, who may be more receptive to cultured meat than plant-based meat (Bryant & Barnett, 2018). Moreover, the growth in plant-based meat consumption is not attributed solely to vegetarians and vegans (McLynn, 2019), which comprise less than 5% of the U.S. population (Reinhart, 2018); this suggests there is demand for alternative proteins, and there will be space in the market for both plant-based and cultured meats.

growing cells in a hydrogel scaffold (McMurtrey, 2016), a back of the envelope calculation considers a glucose concentration of 10–20 mM in the cell media, a diffusion rate of glucose in a hydrogel of 1×10^{-10} m^2/s, and glucose consumption of mammalian cells from 10^{-16} to 10^{-17} mol/L•s. Considering that 100 g of meat contains $\sim 3 \times 10^{10}$ cells (Allan, De Bank, & Ellis, 2019), and is typically ~70% water (Offer et al., 1989), the maximum viable thickness of tissue is estimated to range from 400 to 1400 μm. However, this estimate of tissue thickness depends on various assumptions of cellular metabolic rates and passive diffusion of molecules in the absence of flow. Future experimental and computational work could refine our understanding of the metabolic rates of myocytes and myotubes as well as how scaffold and bioreactor design could be optimized to enable the growth of thicker cuts of meat.

It will also be important to advance methods to optimize cultured meat flavor. To enhance flavor, compounds such as heme, which is contained in the blood-proteins hemoglobin and myoglobin, could be added as a media supplement. Hemoglobin and myoglobin added to cell culture media can also improve cultured meat color (Simsa et al., 2019), which is another important factor for consumer acceptance of meat (Jeremiah, Carpenter, & Smith, 1972). Cyclopentanones are also key contributors to meaty flavor (Mottram, 1991). Many desirable flavors and colors arise during the cooking of raw meat, specifically due to Maillard reactions that occur—for example between amino acids and sugars of cells—and are important for meat flavor due to formation of compounds including pyrazines (nutty, roasted flavor), and furans (caramel like, sweet flavor) that can form through the degradation of carbohydrates, which occurs with cooking (Mottram, 1991). Thermal oxidation of molecules also creates desirable "meaty" flavors, such as 2-methylpropanal (brothy, meaty) and 3-methylbutanal (yeasty, salty, earthy) (Frank et al., 2016). Since many important flavor compounds are lipophilic (de Roos, 2005), the incorporation of fat into cultured meats may additionally be important for flavor. For example, unsaturated phospholipids typically found in intramuscular fat contain linoleic acid and arachidonic acid, which upon cooking oxidize to produce key flavor and aroma compounds such as 2-nonenal (grassy), 2,4-decadienal (fatty), as well as *trans*-4,5-epoxy-(E)-2-decenal (metallic) and

1-octen-3-one (metallic) (Elmore, Mottram, Enser, & Wood, 1999). At cooking temperatures, interactions between unsaturated fatty acids and hydrogen sulfides also result in thiopenes (meaty flavor), which are another important flavor component of meat (Mottram, 1991). Fat and lipophilic flavor compounds could be integrated into cultured meat through fat-producing adipocytes and/or fat encapsulation (Box 2) (Fish, Rubio, Stout, Yuen, & Kaplan, 2020). The extent to which the flavor of cultured meat is determined by compounds naturally occurring in cellular components of meat and/or may be tuned by adding supplemental compounds to the culture media will be an important topic for future investigation.



Barrier: Morality, disgust, and perceptions of naturalness. Consumers not only worry that cultured meat will not taste good—they actually fear it will be disgusting (Verbeke et al., 2015). Philosophers highlight the importance of such "gut feelings," and argue that they warrant special attention (van der Weele & Driessen, 2013). Disgust reactions may reduce consumer acceptance in unique ways compared to the effects of other barriers—such as beliefs that cultured meat is flavorless or unhealthful (Hocquette et al., 2015)—and impede acceptance even if consumers are motivated by animal welfare concerns (van der Weele & Driessen, 2013). The evolutionarily adaptive function of disgust is clear: to avoid ingesting potential contaminants (Rozin & Fallon, 1987). The violation of naturalness is the primary offense of cultured meat that evokes disgust (Bryant & Barnett, 2018; Wilks & Phillips, 2017). Such violations elicit emotionally charged moral judgments of those foods as disgusting, ultimately making individuals deem them unsuitable for consumption. A possible solution to overcome this barrier is to communicate the naturalness of cultured meat. As can be seen in Box 1, a major goal of the field is to generate a cultured beef steak that is made from the exact beef cells that make up a regular steak. Moreover, consumers may not currently have full information on existing farming practices. To enable people to make informed food choices, they could be provided information on the unnatural processes that can be used in modern farming to produce a steak, such as concentrated animal feeding operations and chemical use to accelerate growth. A study of over 1000 participants sampled to match the demographics of the U.S. tested different types of messages regarding cultured meat. Findings showed that arguing for the unnaturalness of conventional meat—using statements such as, "Animals are fed antibiotics and hormones so that they grow much faster and larger than they would in nature"—improved consumer acceptance of cultured meat more than arguing for the naturalness of cultured meat—as in, "The development of clean meat resembles how muscles naturally grow within an animal very closely. In fact, this process of cell growth is present in all natural life" (Bryant, Anderson, Asher, Green, & Gasteratos, 2019).

Behavioral science could also be harnessed to approach consumers on moral and ethical terms. For example, humans are motivated to have moral consistency (Blasi, 1983), and therefore messages could highlight how consuming cultured meat is consistent with peoples' other moral values. As most individuals do not like to harm animals (Loughnan, Bastian, & Haslam, 2014), cultured meat could be viewed positively since it is not coming at the expense of an animal's life: cultured meat involves taking a biopsy from one living animal to retrieve adult muscle stem cells, whereas conventionally produced meat involves the slaughtering of an entire animal. While there still may be ethical concerns with using live animals as a cell source (Schaefer & Savulescu, 2014), the benefits of reducing the slaughtering of animals may outweigh these concerns (Laestadius, 2015). The ethical benefits of having a positive impact on one's carbon footprint could also be emphasized. Currently, there is very low awareness of the impact of conventional meat consumption on the environment (Hartmann & Siegrist, 2017), making this a potentially effective strategy.

Barrier: Cost. Concerns regarding the potentially high cost of cultured meat were also identified in a survey of U.S. consumers (Wilks & Phillips, 2017). Here, technological solutions will be necessary. As the cost of manufactured goods tends to significantly decrease as processes are scaled (Rajagopal et al., 2017), developing scalable processes to produce cultured meat is a major priority. Strategies to culture meat that rely on the inherent self-assembling properties of materials—drawing on soft matter physics—to generate scaffolds and spatially organize meat components could be both scalable and cost effective. Harnessing the natural scaffold structure of plants, fungi, and byproducts of the food supply chain, is another promising approach that could reduce costs of source ingredients (Fig. 1, Box 1). For example, decellularized apple provides a highly porous cellulose structure, which supports the growth of mammalian cells (Modulevsky et al., 2014). However, the question still remains of how scalable this approach is to generate cultured meat with defined spatial structure.

The cell source is another issue to address in terms of cost and scalability. Skeletal muscle satellite cells are a common precursor currently being used in research since they can proliferate in culture and are committed to a muscle cell lineage (Box 1). However, unless cell lines are immortalized, they have a limited number of divisions that cap their proliferative state in culture (Hayflick, 1965), and thus hinder scalability. Using pluripotent cell lines is also of interest, and it is well understood how to tune physical and soluble cues in the cellular microenvironment to drive differentiation into specific lineages needed for cultured meat (Engler, Sen, Sweeney, & Discher, 2006); such an approach could enable patterning multiple cell types into cohesive 3D tissues that contain fat and vasculature. The ability of pluripotent stem cells to differentiate to multiple cell lineages, including myocytes, adipocytes, and fibroblasts, makes this cell type an attractive option. In addition, the ability to reprogram somatic cells into induced pluripotent stem cells (iPSCs) increases options for generating complex cuts of meat that contain different cell types with minimal harvesting from animals. There has been significant progress towards scaling up stem cell culture by optimizing bioreactor design and culture conditions (Abecasis et al., 2017; Li et al., 2020; Villiger et al., 2018). However, there are still challenges and concerns such as differentiation efficiency and remnant undifferentiated and/or tumorigenic cells (Archacka et al., 2018), as well as specific challenges in generating bovine iPSCs (Pillai et al., 2019), which could hinder cultured meat applications. The cost-effective, large-scale production of edible muscle cells remains a major challenge in the field.

One major contributing factor to the cost of cultured meat is the use of animal serum in media formulations. Identifying sustainable substitutes for fetal bovine serum, which is a common growth factor supplement in cell media, will be key to advancing progress towards sustainable cultured meat production. Efforts are ongoing to develop serum-free media for applications in cultured meat to reduce costs and eliminate the need for fetal-sourced ingredients (Kolkmann, Post, Rutjens, van Essen, & Moutsatsou, 2020). As cost-effective media formulations that robustly reproduce the effects of serum in cell culture medium are developed and production scales, the cost of cultured meat is expected to decrease dramatically (Specht, 2019). While cultured meat may initially be offered at a higher price than conventional meat, costs could decrease as production scales as has been observed for renewable energy technologies (Rajagopal et al., 2017).

To fully achieve scaled-up, cost-effective production of cultured meat requires the development of efficient bioreactor systems (Allan et al., 2019). The form of the final cultured meat product is a major factor impacting bioreactor design. For example, the first cultured meat products to market are likely to be blended 3D structures that are produced from muscle cells grown on microcarriers, which have been widely used in analogous industries and are established for scaled-up culture of mammalian cells (Bodiou et al., 2020). The scalable production of structured 'cuts' of cultured meat requires further innovations including for the design of bioreactors, compatible scaffolds, and media formulations. Since cellular behaviors such as adhesion and proliferation depend on both physical and soluble cues, media, scaffolds, and bioreactors should be synchronously developed. For example, cell-scaffold complexes must withstand the fluid shear stresses of continuous culture in a bioreactor, and serum contains proteins that support the adhesion of cells to the extracellular matrix (Klebe, 1974).

Beyond cost concerns, there likely will be value concerns—that high costs balanced against poor taste and other potential drawbacks will result in low value. Potential drawbacks include factors that we have identified as barriers in this Review, as well as those already known in consumer science research, such as switching costs (the hassle, time, and effort of adopting a new product) (Jones, Mothersbaugh, & Beatty, 2002). Indeed, one study found that given equivalent pricing only 11% would purchase a cultured meat burger compared to 65% who would purchase a beef burger (Slade, 2018), indicating that simply solving cost concerns is insufficient.

Barrier: Health and safety. Consumers are worried about the safety of cultured meat (Bryant & Barnett, 2018). A major issue with culturing cells is potential contamination by disease-causing bacteria, mycoplasm, viruses, or fungi. Developing bioreactors that support the large-scale growth of cells on scaffolds with aseptic requirements is another major research priority. Contamination in a well-controlled bioreactor could be screened in real-time to contain and prevent spreading, unlike in a cattle ranch or in conventional beef processing, where meat from a diseased animal may comingle with others before awareness of contamination.

Consumer fears about safety may be mitigated by knowledge of proper government oversight. In 2019, the U.S. Department of Health and Human Services, the Food and Drug Administration, and the U.S. Department of Agriculture (USDA) entered into a formal agreement regarding oversight of cultured meat (or, in their parlance, "human food produced using animal cell culture technology"), which stipulated that all cultured meat must bear a USDA mark of inspection; such an official mark might allay consumer fears (USDA Press Release, 2018).

Beyond safety, however, health concerns related to meat—especially red meats—are not necessarily unfounded. Diets containing red meat are associated with increased risk of cardiovascular disease, cancer, and obesity (Willett et al., 2019). However, the ability to engineer cultured meats could provide opportunities to tune nutritional profiles by increasing the content of unsaturated fats, or even reducing levels of saturated fats; in this way, technology could be harnessed to make meat more healthful. As with the health concerns of unfamiliar ingredients contained in plant-based meats (Box 2), there may be similar concerns for cultured meats. However, the development of edible scaffolds for cultured meat production (Ben-Arye et al., 2020; MacQueen et al., 2019; Orellana et al., 2020) could counter doubts that unfamiliar additives are compromising the naturalness and nutritional quality of cultured meat products (Siegrist & Sutterlin, 2017).

Barrier: Demographic and cultural factors. Not all individuals are alike, and demographic differences can represent both barriers and opportunities for consumer acceptance of cultured meat. For example, men are less receptive than women to eating a plant-based diet (Rosenfeld, 2018), but they are more receptive than women to eating cultured meat (Wilks & Phillips, 2017). However, some demographic groups will likely be less receptive to cultured meat. To overcome potential barriers in less receptive groups, behavioral science can help to identify dietary motivations and values that various social groups prioritize (Hopwood, Bleidorn, Schwaba, & Chen, 2020); this could ultimately inform dissemination efforts to form more inclusive, and thus effective, informational campaigns. Negative emotional reactions, particularly disgust, are more likely to be amplified among people who are socially conservative (Graham, Haidt, & Nosek, 2009), which may in part explain why conservatives are more skeptical of cultured meat than liberals (Wilks & Phillips, 2017). Although they are more skeptical, social conservatives are a segment of the population where major inroads could be made because conservatism is positively correlated with meat consumption (Dhont & Hodson, 2014). Thus efforts should be expended to empirically test persuasion strategies in this group. For social conservatives, campaigns emphasizing the environmental benefits of cultured meat are likely to fail. One study of Americans found that scientific information about climate change backfired in Republican skeptics of climate change, actually reducing support for mitigation policies (Ma, Dixon, & Hmielowski, 2019). We suggest instead to test informational campaigns emphasizing that cultured meat is "real" meat, with the hypothesis that this will result in conservatives viewing cultured meat as an attractive alternative to plant-based meat or vegetarianism.

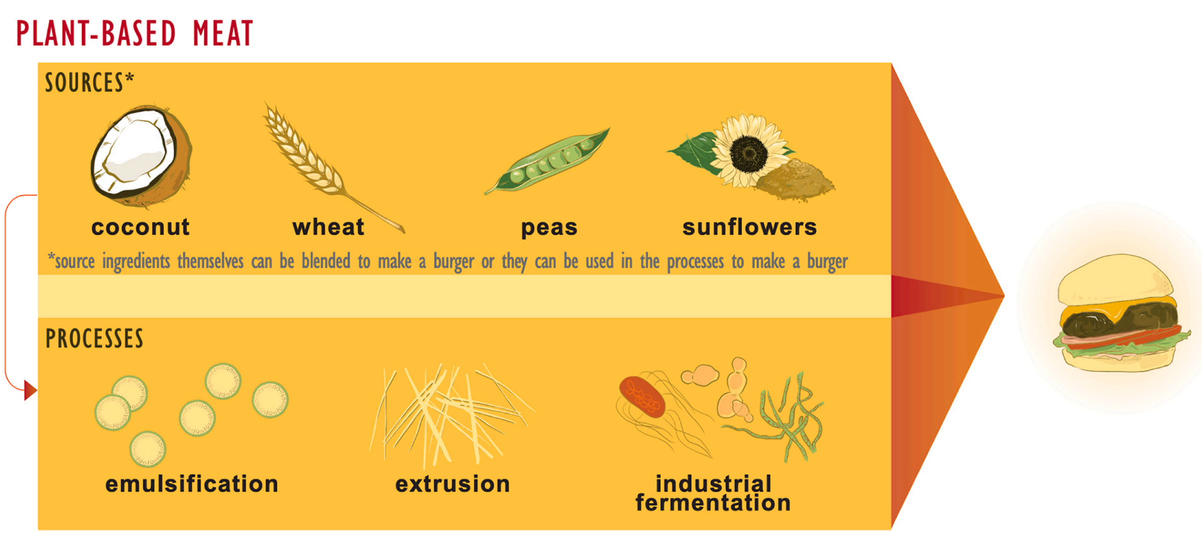
Meat plays a central role in some cultural traditions (Axelson, 1986), which may comprise a barrier to the adoption of cultured meat. There are additional issues to be resolved regarding whether cultured meat would be Kosher or Halal (Chriki & Hocquette, 2020), which would have an enormous impact on consumption across different religions. With due respect to cultural traditions and rituals surrounding meat, we refrain from offering a "solution" to overcome this barrier.

Barrier: Social ethics. A moral objection that has been raised against cultured meat is that it will take jobs away from farmers (Wilks & Phillips, 2017). Policy changes will be necessary to counteract this negative (yet perhaps accurate) perception. Analogous to autoworkers and other industries vulnerable to outsourcing, governments could use policy to protect farmworkers in the meat industry. It is important to highlight that cultured meat production will also generate higher-skilled and therefore relatively higher-paying jobs (Stephens et al., 2018).

Barrier: Mistrust of science. While we have highlighted how science and technology could address several barriers to cultured meat consumption, negative perceptions of science and technology can impact food choices (McCluskey, Kalaitzandonakes, & Swinnen, 2016). For many people, science seems inaccessible and unfamiliar (Sinatra & Hofer, 2016), which could further exacerbate food neophobia. To improve consumer perceptions, behavioral science could guide how to introduce these products to market. Consumers are more willing to buy cultured meat when it is described with nontechnical rather than technical terminology (Siegrist, Sutterlin, & Hartmann, 2018). Labeling a product as "clean meat" increases acceptance relative to labeling the product as "lab-grown meat" (Bryant & Barnett, 2019). Any terminology ultimately adopted, however, should be vetted to protect against potential unintended consequences. For example, "clean" meat may incite suspicion amongst consumers who are prone to distrust food companies (Mohorcich & Reese, 2019) that the term is intended to whitewash or obscure an unsavory origin. Further research on marketing strategies is necessary in cooperation with companies that will bring these products to market as well as meat interest groups.

We assert that providing transparent scientific communication on cultured meats will be critical. The introduction of foods that rely heavily on science and technology—a prime example being genetically modified organisms (GMOs)—can be faced with skepticism and rejection. A major driver of the public skepticism about GMOs stemmed from the powerful role of agri-business in their promotion (National Academies of Sciences Engineering and Medicine, 2016). For this reason, the role of academics in conducting unbiased research and effectively communicating science-based facts to the public will be critical. Academia is not profit-driven, and researchers strive to publish findings rather than keep trade secrets. Indeed, perceptions that GMO manufacturers were being secretive was one factor that led to consumer resistance against GMOs (Mohorcich & Reese, 2019). Thus, in contrast to private corporations, academia is an ideal conduit for information about cultured meat to reach the public. Highlighting the inherent differences in motivation between private food companies and academia is one strategy that could be used to increase public acceptance, much as the truth® campaign highlighted the motivations of cigarette companies (as opposed to the health threats of cigarettes themselves) (Farrelly, Nonnemaker, Davis, & Hussin, 2009).

One effective path to increase consumer knowledge could be through the education system. Emerging evidence shows that curricular interventions can promote shifts toward reduced meat consumption. A recent study surveyed student diets before and after an environmental science course taught through the lens of food, "Food: A Lens for Environment and Sustainability" (Jay et al., 2019). The class, which fulfilled general education requirements, covered topics such as biodiversity, climate regulation, and climate change. Students completed assignments where they calculated the carbon cost of producing a grocery store item and made a short film or performance to disseminate their findings to a general audience (Jay et al., 2019). After six months of instruction, the dietary carbon footprint of the intervention group was approximately 1000 g CO_2.eq per day lower than the comparison group that took the class "Evolution of the Cosmos and Life"—a science course that also fulfilled general education requirements. If these modest dietary shifts could be extrapolated across the U.S. population, the GHG savings would amount to a third of the total emissions reduction needed to achieve the goals in the Paris Climate Agreement set within the 2015 United Nations Framework Convention on Climate Change (Jay et al., 2019). In addition to curricular interventions, researchers can directly communicate the science of cultured meat to public audiences. For example, academics can engage in discussion with the public through media including print, radio/podcasts, and television, as well as social media. Events such as panel discussions or science cafés can provide perspectives from experts on topics including engineering, behavioral sciences, public policy, and environmental science to further engage the public in dialogue about the potential and concerns of cultured meat. At our own institution, the Science&Food organization provides a model for events that create dialogue with public audiences on timely food-related topics (Rowat, 2013). Such efforts could be focused on breaking down barriers we have identified in this Review. For example, one target for science communication could be to clarify that some additive ingredients in cultured meats (Box 2) are naturally occurring molecules; there are widespread negative misconceptions that unfamiliar molecules—such as naturally occurring cellulose—should be avoided (Pollan, 2009). The emergence of cultured meats provides an exciting opportunity to engage with consumers effectively and transparently, and to even enrich the public understanding of science.



Change is possible. Despite these barriers, we are optimistic that widespread adoption of cultured meats is possible, even if that requires a shift in larger cultural norms. Incorporating messaging about increases in acceptability of meat alternatives may be effective, given evidence that dynamic norms—those that communicate a changing of opinions—can precipitate change even in the face of socially entrenched norms (Sparkman & Walton, 2017). Indeed, at least one very recent study indicated potential for a positive response to cultured meat. A study conducted in the Netherlands offered participants samples of two identical conventional beef burgers but labeled one of them as "cultured" meat. Of the two, participants deemed that the meat with the "cultured" label tasted better, and were willing to pay 37% more for cultured meat (Rolland, Markus, & Post, 2020). A rapid emergence of start-ups — and the concomitant exposure brought by their marketing campaigns—could play a pivotal role in shaping public perceptions of cultured meat (Choudhury, Tseng, & Swartz, 2020).

Because self-control is difficult and effortful, approaches that bypass self-control processes may also be effective for long-term change. Once cultured meat products have come to market, a behavioral economics approach that involves "nudging" could represent an attractive alternative to exercising willpower that also avoids backlash (Ferrari, Cavaliere, De Marchi, & Banterle, 2019). Nudges might be as small as placing cultured meats at eye level in the grocery store, or as large as changing the default meat to cultured meats and instead framing the choice to eat conventional meat as an alternative (Ferrari et al., 2019).

Conclusion. Cultured meat is an exciting food frontier that holds promise for human and planetary health. By proactively addressing negative consumer perceptions using a full arsenal of behavioral science, technology, science communication, and policy, we can be poised to harness the promise of cultured meat to reduce the environmental impact of the human diet.

Author's contribution

All authors contributed to the writing and editing of this manuscript.

Declaration of competing interest

ACR was a Scientific Advisory Board member for Beyond Meat and holds stock options in the company.

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