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Not getting laid: consumer acceptance of precision fermentation made egg

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Mounting concern over the negative externalities of industrialized animal agriculture, coupled with falling cost curves of novel food technologies have birthed the field of cellular agriculture: a new category of food technology seeking to reproduce the sensory experiences of animal protein, and promising a cleaner, more ethical way of enjoying animal proteins. This research examines consumer acceptance of precision fermentation (PF) made egg products in Germany, Singapore, and the USA. Using an online survey of 3,006 participants, the study examines demographic and dietary traits that predict willingness to try such products and identifies the reasons why consumers are most attracted to them. The findings suggest that PF made egg products are likely to find a willing market, with a substantial proportion (51–61%) of participants willing to try the product, with vegetarians and vegans displaying the highest enthusiasm. Egg consumption habits and, to a lesser extent, income also predict acceptance. Major reasons for adopting the product were animal welfare in Germany, and health aspects in Singapore and the USA, as well as curiosity in all three countries. Observed differences between the acceptance of PF egg and PF dairy are discussed, as well as comparisons to existing alternative protein (AP) product adoption.

KEYWORDS

precision fermentation, cellular agriculture, fermentation, consumer acceptance, food system

Introduction

Having risen by nearly 70% since the 1960s (FAO, 2023), humanity's consumption of animal protein is becoming an increasingly destabilizing force acting on the planet's climate, and itself a victim of mounting instability. The impacts of rising temperatures and extreme weather events are already impacting the productivity of the agri-food sector (Lesk et al., 2016), with economic volatility, exposed global supply chains and the proliferation of animal-borne diseases providing further threats to the stable supply of animal protein (Sundström et al., 2014).

The livestock industry itself drives much of this instability, producing an estimated 14.5% of global greenhouse gas emissions (Gerber et al., 2013). It is also a leading cause of air and water pollution, deforestation, and water scarcity (Rojas-Downing et al., 2017). Furthermore, the livestock industry is the leading cause of emerging zoonotic diseases such as avian-flu and swine flu (Hayek, 2022), as well as being the leading risk factor for future antibiotic resistance, forecast as one of humanity's greatest emerging threats in the 21st Century (UNEP, 2020). Though public awareness of the severity of the livestock industry's negative aspects has grown

recently (Janssen et al., 2016), the critique of our relationship with animals is longstanding, especially from an animal-welfare perspective, with the roots of veganism and vegetarianism laced through religious and philosophical axioms that are millenia-old (Whorton, 1994). As the tools of industrialized, globalized economies blend with humanity's rapidly growing appetite for animal-based protein, increasingly productive, albeit increasingly demeaning conditions for animals have become the global norm (D'Silva, 2006). Hence, there arises a compelling argument for reconsidering our relationship with livestock, diversifying our global protein supply, and heavily reducing our consumption of animal-based proteins.

While not garnering the same focus as meat or dairy (Spain et al., 2018), the humble egg is an optimal vessel to understand the nature of animal protein consumption in the 21st century, along with a corresponding need to change our relationship with it. Driven by selective breeding, optimized feeding and living conditions, and an increasing consumer desire for animal protein, egg production has risen from 1961 levels of 15 million tonnes annually, to over 93 million tonnes in 2020 (FAO, 2020). Though standard chickens now produce around 300 eggs per year (as opposed to the 40 eggs that chickens historically produced in natural settings) (ProVeg International, 2018), a more developed egg production system has, ironically, not insulated consumers from price swings or shortages. Instead, consumers face greater volatility, with global commodity prices, diseases and labor shortages now all directly feeding through to contemporary egg markets (Lorsch, 2023).

While the carbon emissions profile of eggs are less damaging when compared to that of cheese or meat (in part due to the hugely adapted genetic and environmental conditions of modern day chickens), producing around 4.67 kg of CO2-e per 100 g of protein produced (Ritchie et al., 2022), industrial egg production is a leading contributor toward biodiversity loss and localized environmental pollution, with chicken effluent containing high levels of nitrogen and phosphorous (Basitere et al., 2019). This leads to algal superblooms and catastrophic effects for local wildlife populations when running-off from agricultural fields (Han et al., 2017). In the same way, chicken feed accounts for 37% of global soy production (Ritchie and Roser (2021), which acts in turn is a major driver of global biodiversity loss (WWF, 2014).

Recognizing the moral, environmental and practical concerns surrounding animal-product consumption, consumers and policymakers are already examining ways to reduce the consumption of animal-based protein, with the provision and promotion of alternative proteins (APs) earmarked as one of the most feasible means to achieve this (IPCC, 2022). Both plant-based meat and dairy products have made substantial market inroads in the last decade, turning both into multi-billion dollar industries (Good Food Institute, 2023a), though their inability to fully replicate the sensorial experiences and functionality of animal products has left many consumers unwilling to fully remove animal products from their diets.

The emergence of cellular agriculture, a field of research that uses cellular and molecular biology to produce agricultural products from cell cultures, was born from a recognition of this predicament and endures as an attempt to address it. Combining the tools of molecular biology, biochemistry and engineering, cellular agriculture seeks to develop products structurally and functionally identical to those made by animals, yet without animal exploitation.

An emergent pool of research has started to examine the predicted economic and social impacts of cellular agriculture, particularly engaging with the question of whether and how consumers will adopt this new category of products (Bryant and Barnett, 2020) Cultivated meat, meat grown from biopsied animal cells, has drawn the bulk of this research focus, while precision fermentation (PF), a technology allowing for the creation, not of animal flesh, rather the individual components of animal products, such as milk or egg proteins, is comparatively underexamined.

After the alteration of single-celled organisms' DNA, PF is conducted in brewery-like facilities to produce specific compounds—either modeled on those found in nature, or entirely novel compounds. This approach has been in use for some time to manufacture expensive and complex compounds, such as insulin and rennet but the costs of PF are now dropping to a level that means more and more compounds are becoming economically competitive with those produced by animals (BCG, 2022). Several companies, including the co-authors of this paper, Formo, are now applying PF to create functionally identical egg and dairy proteins, blending these with fats, emulsifiers and water to create products without many of the associated environmental, health and ethical concerns associated with conventional animal protein production. Unlike existing plant-based vegan products, PF products exhibit many of the versatile functional properties associated with animal-derived products, significantly improving end-consumer experience. In the context of a PF egg product, this manifests in properties such as coagulation, emulsification, leavening and binding. Just as with conventional liquid egg or dairy storage, PF made products will need to be safely treated and stored, including suitable refrigeration, pasteurization and packaging to avoid premature spoilage. While initial products will likely debut with an associated price premium, especially in food-service settings, scaled production processes, as well as advances in fermentation efficiency will likely deliver products similar in price to premium eggs in the near future.

Initial life-cycle assessments of egg proteins produced via PF (Järviö et al., 2021) show an advantage in terms of most environmental impacts, such as global warming potential and land usage, while also circumventing the localized environmental damage that industrial egg production causes. Likely future sustainability advances will be driven by advances in production efficiency, renewable energy sourcing and effective side stream usage. PF also reduces the need for antibiotic usage, which, when considering that roughly 70% of US antibiotics are fed to chickens, implies a huge step toward a more future of more restrained antibiotic usage (O'Neill, 2015).

Despite a number of companies seeking to produce egg products through PF, as well as compelling grounds for their adoption, no research has examined the extent and dynamics of consumer acceptance for such products. This dynamic will ultimately determine the impact of cellular agriculture and its ability to reorient our relationship with animal protein. Grassian (2020) found that people who are seeking to lessen their intake of animal products were less likely to avoid eggs and dairy in comparison to other animal-based foods. As such, it is probable that eggs are one of the most difficult food groups to avoid for consumers, pointing both to the weaknesses of existing egg substitute products, and the potential for PF made egg to gain a foothold among existing consumer groups.

Some research has examined consumer acceptance of cheese products made via PF, seeing notably higher enthusiasm than for cultivated meat products [with 70.5% of consumers probably or

definitely likely to buy such a product (Zollman Thomas and Bryant, 2021)], however, how level of enthusiasm, perceptions, audiences, and rationale varies between PF made products is unclear, especially between countries.

Our research therefore addresses the following three research questions:

1. What is the overall level of consumer interest in PF made egg products in Germany, Singapore and the USA?
2. What are the demographic and dietary traits that most strongly predict a willingness to consume a PF made egg product?
3. For what reasons do consumers consider the adoption of a PF made egg most attractive?

Methods

Participants

Across the three countries, a total of 7,938 participants aged 18 to 75 years old were recruited for an online survey through Dynata, a research panel agency. Four interlocking quotas based on gender and age were implemented, with subsequent weightings applied to the samples to produce results that were nationally representative of the population. 4,011 participants across the three countries were not eligible to complete the survey as the age and gender quotas were full. These participants were redirected back to the panel. To enhance data quality, participants who failed the honesty check ($n = 51$) and two attention check measures ($n = 602$) were excluded. Additionally, responses to open ended questions that were generated by bots were manually identified and removed from the survey ($n = 273$). Replacement participants were provided by Dynata. This resulted in a final sample of 1,000 participants from Germany, 1,000 from USA and 1,001 from Singapore (see Table 1 for participant characteristics).

Procedure

Data was collected via an online survey that was administered on Qualtrics. The study was approved by the Institutional Review Board at Singapore Management University. Participants were briefed that the study examined people's perceptions of new types of food products. After informed consent was obtained, participants were asked to indicate their age and gender to control for balanced response rates and to verify that they have met the specific quota requirements in order to continue with the survey. Participants then read a passage about PF, and its use in creating a new egg product. Careful consideration was put into the development of the passage, formulated to both concisely introduce a complex technology, and simulate the setting with which consumers would be likely to encounter the product 'in the wild'. This process will be elaborated on in the Materials section. A timer validation of 15 s was implemented in Qualtrics to ensure that participants spent sufficient time reading the passage.

In the next section, participants were tested on their comprehension of the passage. The first question asked participants the extent to which they understood the new product and what makes it different from existing products. In an open-ended question, participants were then asked if they had any questions about the product and what makes it different from existing products. Participants then had to answer a multiple-choice question which asked what the actual ingredients of the new egg product were. If participants did not select the option of 'proteins made by microorganisms', a quick reminder was displayed to participants which clarified that What Came Third (the name of the new product) is made using real proteins that are created by microorganisms. This was to ensure that all participants had the same baseline understanding of the PF made product.

The following section consisted of questions pertaining to the acceptance of PF made egg and the reasons that would attract participants to purchase this new product.

The next section required participants to answer questions about their dietary habits including their current diet and their frequency of consumption of various egg products. Participants then answered some demographic questions and were debriefed. They were also given an opportunity to comment or ask questions about the research. At the end of the survey, participants answered an honesty check question which asked them if they had responded to the survey in a reasonably careful and honest manner. Lastly, participants were thanked for their time and were redirected to the panel to receive compensation.

Materials

Consumers' introduction to and framing of PF made food has been shown to impact both the acceptability and desirability of PF produced food products (Broad et al., 2022). For this reason, the text introduction of PF produced egg provided to respondents was constructed with a view to present a simple and transparent overview of the technology, product attributes and a rationale for its introduction. This survey sought to create a description that accurately captured the fundamentals of PF, while also focusing on the qualities of the end product that would be consumed by society.

Due to a lack of consensus within industry and regulatory bodies surrounding PF product nomenclature, and to effectively simulate consumers' initial exposure and assessments of PF made egg products, the product was referred to by a product name: What Came Third.

The passage introducing the PF made egg product are as follows:

> *A company is preparing to launch a new egg product. The product cooks, tastes and behaves identically to a real beaten egg, only it is made without any animals involved.*
>
> *For cooking and nutrition, the most important part of an egg is its protein. Instead of using chickens to make this protein, a process similar to beer or soy-sauce production is used, where microorganisms make the ingredients.*
>
> *By precisely changing the DNA of microorganisms, it is possible to turn them into mini-factories that produce specific proteins with the same function, flavor, nutrition and applications as egg protein. This process is called precision fermentation.*
>
> *These proteins are collected and turned into a product that consumers, chefs and bakers can all use to make diverse dishes like*

TABLE 1 Participants' demographic and dietary characteristics across countries in the weighted sample.

	Germany *N*=1,001 *n* (%)	USA *N*=1,001 *n* (%)	Singapore *N*=1,004 *n* (%)
Gender			
Female	540 (53.9%)	521 (52.0%)	480 (47.9.%)
Male	460 (46.0%)	472 (47.1%)	517 (51.6%)
Gender-queer	1 (0.1%)	9 (0.9%)	6 (0.6%)
Age group[1]			
18–24	97 (9.7%)	126 (12.6%)	101 (10.0%)
25–39	262 (26.2%)	287 (28.6%)	283 (28.3%)
40–59	376 (37.5%)	350 (35.0%)	382 (38.1%)
60–75	266 (26.6%)	238 (23.7%)	237 (23.7%)
Degree of urbanization			
Rural area or village	276 (27.6%)	210 (21.0%)	–
Small or medium sized town	366 (36.6%)	423 (42.3%)	–
A city or large city	359 (35.8%)	368 (36.7%)	–
Educational level			
Less than high school	153 (15.3%)	33 (3.3%)	13 (1.3%)
High school	149 (14.8%)	195 (19.5%)	134 (13.4%)
Some college, no degree	19 (1.9%)	207 (20.7%)	241 (24.0%)
Associate degree	394 (39.3%)	110 (10.9%)	37 (3.7%)
Bachelor degree	135 (13.5%)	276 (27.6%)	484 (48.2%)
Master degree	145 (14.5%)	150 (15.0%)	79 (7.9%)
PhD	6 (0.6%)	30 (3.0%)	15 (1.4%)
Yearly household income			
Low	575 (57.5%)	334 (33.4%)	160 (15.9%)
Middle	366 (36.5%)	403 (40.2%)	462 (46.1%)
High	60 (6.0%)	264 (26.4%)	381 (38.0%)
Current diet			
Omnivore	434 (43.3%)	661 (66.0%)	537 (53.5%)
Flexitarian	440 (44.0%)	250 (24.9%)	371 (36.9%)
Vegetarian	78 (7.8%)	27 (2.7%)	55 (5.5%)
Vegan	34 (3.4%)	19 (1.9%)	18 (1.8%)
Others (e.g., No diet, Pescatarian, Halal, Mediterranean, Gluten-free)	15 (1.5%)	45 (4.5%)	23 (2.3%)

[1]Weights were generated based on age group (Refer to Supplementary material for weight calculations).
Degree of urbanization for Singapore participants was not measured as it was assumed that all participants live in the city.
Low income earners: ≤ €49,999, ≤ SGD35,000, ≤ USD39,999.
Middle income earners: €50,000–€99,999, SGD35,001–SGD100,000, USD40,000–$100,000.
High income earners: ≥ €100,000, ≥ SGD100,001, ≥ USD100,000.

> *scrambles, egg-fried rice, quiches and cakes. Not chicken, not egg, but microorganisms making protein, hence the product name: What Came Third.*
>
> *What Came Third does not involve any animals (nor the antibiotics that animals are often fed), does not contain cholesterol and causes less damage to natural ecosystems than industrial egg production.*

With this introduction, the research sought to simulate market conditions where the availability, awareness and understanding of PF egg products is higher than that of today.

After the passage, participants were shown a picture of a beaten egg and two egg dishes: scrambled eggs and omelet for the German and USA surveys, and scrambled eggs and egg fried rice (a favorite local dish in Asia) for the Singapore survey (Figure 1), in order to communicate the functionality and applications of PF made egg, especially distinguishing it from existing plant-based egg substitutes.

The survey was distributed in English for all three countries, and in German for participants in Germany during the period of January to February 2023. The survey was translated into German through a process of back-translation to ensure brevity without compromising on the survey questions' original meanings. This was carried out by

FIGURE 1
Pictures shown to participants when introducing the precision fermentation made product.

native speakers working at Formo, based in Germany. The questions were the same across all three countries, apart from some demographic questions such as degree of urbanization and income to account for country-specific differences.

Measures

Acceptance of PF egg products

Participants rated their willingness to: try this new product, order a dish from a restaurant/food stall made using this new product, purchase this new product in a supermarket, purchase this new product regularly, and their likelihood of visiting a restaurant where guests had the option to substitute chicken egg for this new product. These items were rated on a five-point scale (1 = *definitely not*, 5 = *definitely yes*). The scores of all five items were aggregated to form a composite measure (mean score of all items), where higher scores indicate a higher acceptance of the PF egg product. The scale demonstrated a high level of internal consistency (Germany: $\alpha = 0.95$; USA: $\alpha = 0.94$; Singapore: $\alpha = 0.93$).

Reasons attracting participant to purchase PF egg products

Participants were given a list of 13 reasons and were asked to select the reason that would most attract them to buy this new product (single-response question). The list of reasons was as follows: Less use of antibiotics, better animal welfare, great taste, less environmental impact, curiosity, fits with a vegan diet, use of new technology, no cholesterol, protein content, price, health, no egg allergens, and others. The reasons were presented in random order (except the 'others' option) to prevent any order effects.

Dietary habits

Current diet

Participants were asked to indicate their current diet. The options are as follows: Omnivore ("I eat animal products unrestrictedly"), flexitarian ("I'm trying to reduce my consumption of animal products"), vegetarian, vegan, and others. If participants indicated "carnivore" under the others option, it was re-coded under "omnivore".

Frequency of consumption of various egg products

Participants rated how frequently they consumed four egg products: Organic eggs, free range eggs, normal eggs, and plant-based egg alternative. These items were rated on a six-point scale (*never, less than once a month, one to three times per month, one to three times per week, four to six times per week, every day*).

Demographic variables

Demographic variables like gender, age, highest educational qualification, yearly household income, and degree of urbanization were included in our analyses. Gender was dummy coded with females as the reference category. Age, highest educational qualification (*less than high school, high school, some college no degree, associate degree, bachelor degree, master degree, PhD*), income and degree of urbanization (*a rural area or village, a small or medium sized town, a city or large city*) were treated as continuous variables. It was assumed

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TABLE 2 Frequency of product consumption scores of the weighted sample.

	Range	Germany *N*=1,001 Mean (SD)	USA *N*=1,001 Mean (SD)	Singapore *N*=1,004 Mean (SD)
Frequency of product consumption	1–6			
Organic eggs		2.86 (1.24)	2.26 (1.39)	1.90 (1.23)
Free range eggs		3.09 (1.17)	2.52 (1.37)	2.37 (1.36)
Normal eggs		2.42 (1.32)	3.47 (1.27)	4.05 (1.12)
Plant-based egg alternative		1.58 (1.05)	1.56 (1.13)	1.51 (1.04)

1 = Never; 2 = Less than once a month; 3 = 1–3 times per month; 4 = 1–3 times per week; 5 = 4–6 times per week; 6 = Every day.

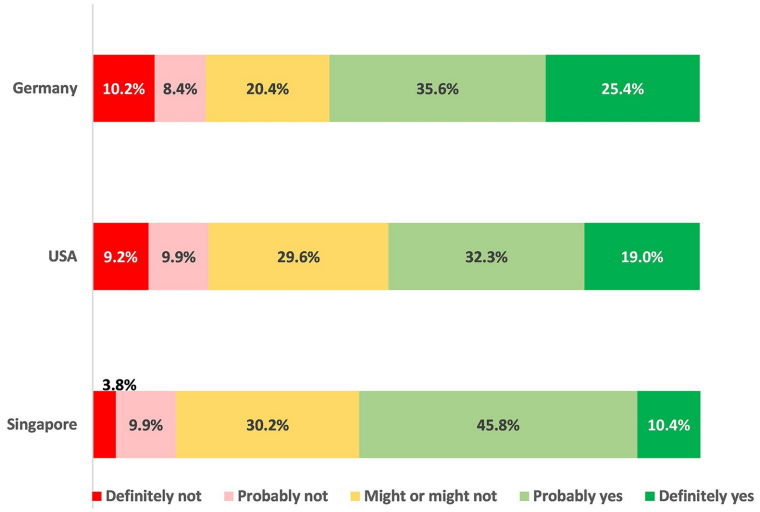

FIGURE 2
Willingness to try precision fermentation egg product across countries.

that all participants from Singapore lived in the city as there are close to no rural areas in the nation. Income was measured on a six-point scale for Germany (1 = *less than €25,000*, 6 = *€125,000 or more*) and USA (1 = *Less than USD20,000*, 6 = *USD125,000 or more*) and on an eight-point scale for Singapore (1 = *SGD15,000 or less*, 8 = *More than SGD150,000*). For our analyses, income was re-coded into three main categories for all three countries: low, middle and high.

Results

Demographic and dietary characteristics

We conducted all analyses with IBM SPSS Statistics 28.0. Samples were weighted to be nationally representative of the population in terms of age groups. Median annual income levels of the weighted samples closely corresponded to that of the population for the three countries (Bundesagentur für Arbeit, 2021; United States Census Bureau, 2022; Singapore Department of Statistics, 2023a). As for education, upper secondary school completion (high school and above) and the proportion of participants living in urban areas (small or medium sized town or a city or large city) closely corresponded to national figures for Germany and USA (World Bank, 2021; OECD Better Life Index, 2023). In Singapore, only 1.3% of the weighted sample did not complete high school education. This was below the national figure of 21% (Singapore Department of Statistics, 2023b). Hence, the post-weighted samples in Germany and USA were broadly representative of society in terms of education and degree of urbanization.

In terms of dietary characteristics, a large number of participants in Germany identified as flexitarians (44%) while the majority of participants identified as omnivores in USA (66%) and Singapore (53.5%). Germany also had the highest consumption frequency of organic ($M = 2.86$, $SD = 1.24$), free range ($M = 3.09$, $SD = 1.17$) and plant-based eggs ($M = 1.58$, $SD = 1.05$), followed by USA and Singapore, while Singapore had the highest consumption frequency of normal eggs ($M = 4.05$, $SD = 1.12$), followed by USA ($M = 3.47$, $SD = 1.27$) and Germany ($M = 2.42$, $SD = 1.32$; Table 2).

Acceptance of PF egg across countries

High acceptance levels of the PF egg product were seen across countries (Figures 2, 3). Around half of the total weighted sample were probably or definitely willing to try (56.1%) and purchase (51%) the product from the supermarket. Germany had the highest levels of willingness to try (61%) and purchase (57.2%) the product, followed by Singapore (try: 56.2%; purchase: 48.1%) and USA (try:

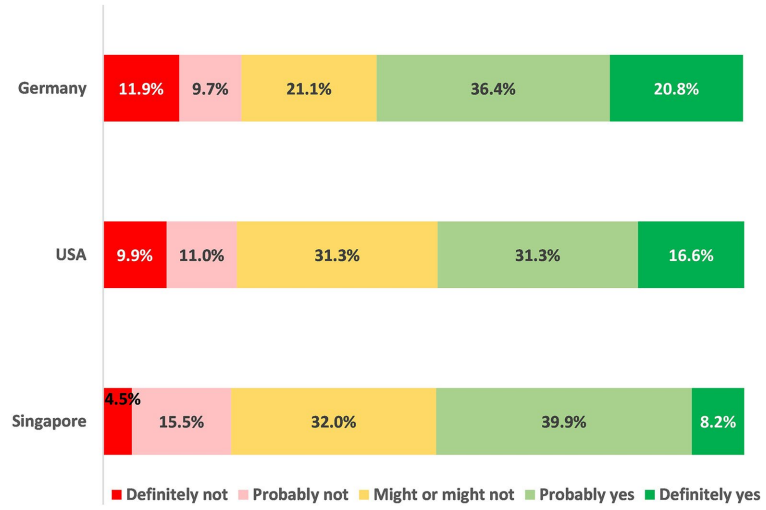

FIGURE 3
Willingness to purchase precision fermentation egg product across countries.

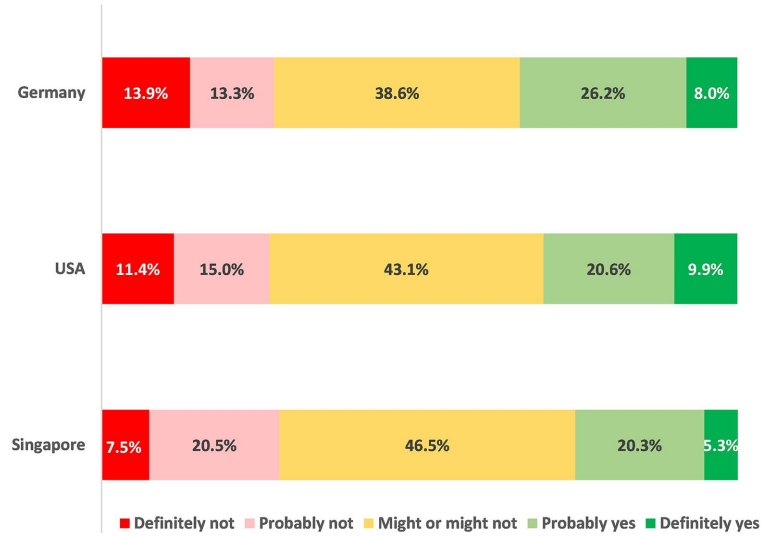

FIGURE 4
Willingness to regularly purchase precision fermentation egg product across countries.

51.3%; purchase: 47.9%). Singapore had lower levels of outright rejection but also lower levels of those who considered themselves definitely willing to try (10.4%) and purchase (8.2%) the product. Levels of willingness to purchase the product regularly were low across the three countries, with a large number of participants from the total weighted sample (42.7%) not knowing whether they might or might not purchase the product regularly (Figure 4).

The next part of product acceptance examined participants' willingness to order a dish from a restaurant/food stall made using this new product and their likelihood of visiting a restaurant where guests had the option to substitute chicken egg for this new product (Figure 5). The pattern of results was similar, with Germany leading in willingness to order a dish from a restaurant/food stall (55.1%), followed by Singapore (53.6%) and USA (46.7%). A higher proportion of Singaporeans were probably or definitely likely to visit a restaurant where guests had the option to substitute for this new product (46.9%), compared to Germany (43.9%) and USA (42%).

The effect of country on product acceptance of PF egg

A one-way ANOVA was conducted to examine the effect of country on product acceptance (Table 3). There were no significant differences between countries on overall product acceptance (composite score; *Welch's F* (2, 1974.13) = 1.24, $p = 0.288$) and willingness to purchase the product regularly (*Welch's F* (2, 1990.14) = 1.39, $p = 0.251$) in the weighted sample. There were significant differences between countries

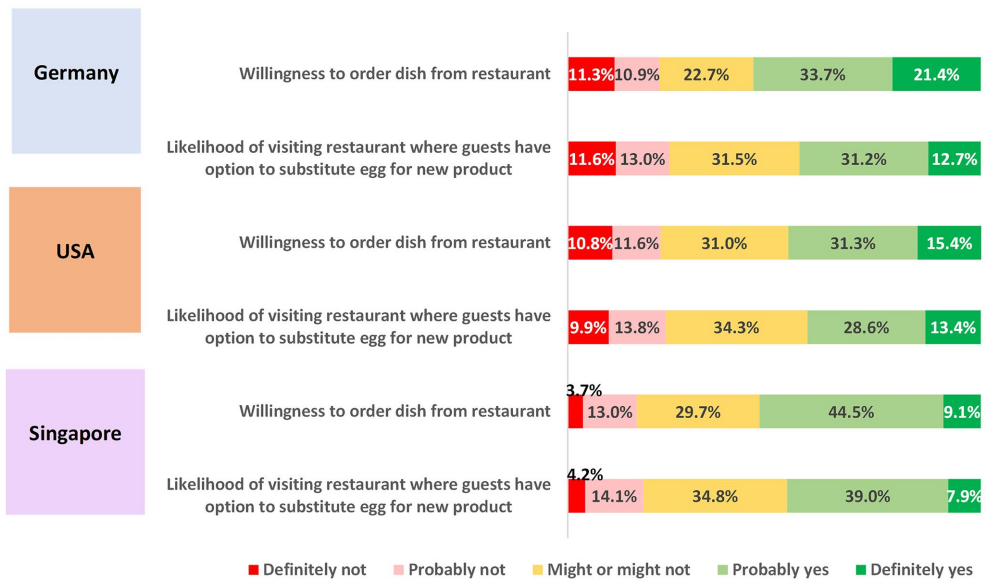

FIGURE 5
Willingness to eat precision fermentation egg product in restaurants across countries.

on willingness to try (*Welch's F* (2, 1969.60) = 4.18, $p = 0.016$), willingness to order the dish from a restaurant/food stall (*Welch's F* (2, 1971.44) = 4.69, $p = 0.009$), willingness to purchase the product from a supermarket (*Welch's F* (2, 1977.97) = 3.42, $p = 0.033$) and the likelihood of visiting a restaurant where guests have the option to substitute egg for the new product (*Welch's F* (2, 1982.79) = 3.99, $p = 0.019$).

Games-Howell post-hoc tests revealed than participants from Germany ($M = 3.57$, $SD = 1.24$) were significantly more willing to try the product as compared to participants from USA ($M = 3.42$, $SD = 1.17$, $p = 0.011$). Participants from USA ($M = 3.29$, $SD = 1.18$) were also significantly less willing to order a dish from a restaurant made using this new product as compared to those in Germany ($M = 3.43$, $SD = 1.25$, $p = 0.028$) and Singapore ($M = 3.42$, $SD = 0.96$, $p = 0.015$). Additionally, participants from Germany were significantly more willing to purchase the product from the supermarket ($M = 3.44$, $SD = 1.25$) as compared to participants from Singapore ($M = 3.32$, $SD = 0.98$, $p = 0.030$). However, participants from Singapore were significantly more likely to visit a restaurant where guests have the option to substitute egg for the new product ($M = 3.32$, $SD = 0.96$) as compared to those in Germany ($M = 3.21$, $SD = 1.17$, $p = 0.035$).

Dietary and demographic predictors of acceptance

To investigate if demographic and dietary variables may explain acceptance of the product across countries, a three-step hierarchical multiple regression was conducted within each country. Demographic variables (i.e., age, gender, income, degree of urbanization,[1] education) were entered in Step 1 of the regression. Current diet[2] (flexitarian, vegetarian, vegan and others) was entered in Step 2 and frequency of consuming various egg products (organic, free range, normal, plant-based eggs) were entered in Step 3 (Table 4). At each step of the model, we assessed the percentage of variance explained by the explanatory variables by calculating the model R^2. We also compared subsequent steps of the model to the previous steps (i.e., Step 2 vs. Step 1, Step 3 vs. Step 2) using ANOVA F-tests to determine if including additional variables significantly improved the explanatory power of the model.

In Step 1, we found that demographic variables predicted a significant amount for variance in product acceptance for all three countries (Germany: $R^2 = 0.045$, F (5, 995) = 9.49, $p < 0.001$; USA: $R^2 = 0.056$, F (5, 995) = 11.84, $p < 0.001$; Singapore: $R^2 = 0.036$, F (4, 999) = 9.29, $p < 0.001$).

Including diet in Step 2 improved the model significantly (Germany; $\Delta R^2 = 0.139$, ΔF (4, 991) = 42.11, $p < 0.001$; USA; $\Delta R^2 = 0.055$, ΔF (4, 991) = 15.34, $p < 0.001$; Singapore; $\Delta R^2 = 0.036$, ΔF (4, 994) = 9.71, $p < 0.001$).

Adding the frequency of consumption of various egg products in Step 3 further improved the model significantly (Germany; $\Delta R^2 = 0.032$, ΔF (4, 987) = 10.04, $p < 0.001$; USA; $\Delta R^2 = 0.075$, ΔF (4, 987) = 22.62, $p < 0.001$; Singapore; $\Delta R^2 = 0.064$, ΔF (4, 990) = 18.27, $p < 0.001$). In combination, the predictor variables explained 21.6% of the variance in product acceptance in Germany, 18.6% in USA and 13.6% in Singapore. We will report the results from Step 3 for concision.

In Germany, older ($B = -0.01$, $SE = 0.00$, $p < 0.001$) and higher educated participants ($B = -0.04$, $SE = 0.02$, $p = 0.032$) predicted lower acceptance of the product. However, higher educated participants in USA were more likely to accept the product ($B = 0.06$, $SE = 0.02$,

1 Degree of urbanization was not included in the regression analyses for Singapore.

2 Current diet was dummy coded with 'omnivore' serving as the reference category.

TABLE 3 One-way ANOVA showing between-country differences in product acceptance of precision fermentation egg for the weighted sample.

	Germany Mean (SD)	USA Mean (SD)	Singapore Mean (SD)	ANOVA
Composite score	3.33 (1.11)	3.26 (1.04)	3.30 (0.85)	*Welch's F* (2, 1974.13) = 1.24, $p = 0.288$
Willingness to try	3.57 (1.24) ^{U}	3.42 (1.17) ^{G}	3.49 (0.94)	*Welch's F* (2, 1969.60) = 4.18, $p = 0.016$*
Willingness to order dish from restaurant	3.43 (1.25) ^{U}	3.29 (1.18) ^{GS}	3.42 (0.96) ^{U}	*Welch's F* (2, 1971.44) = 4.69, $p = 0.009$**
Willingness to buy	3.44 (1.25) ^{S}	3.34 (1.17)	3.32 (0.98) ^{G}	*Welch's F* (2, 1977.97) = 3.42, $p = 0.033$*
Willingness to buy regularly	3.01 (1.13)	3.03 (1.10)	2.95 (0.96)	*Welch's F* (2, 1990.14) = 1.39, $p = 0.251$
Likelihood of visiting restaurant where guests have option to substitute egg for new product	3.21 (1.17) ^{S}	3.22 (1.15)	3.32 (0.96) ^{G}	*Welch's F* (2, 1982.79) = 3.99, $p = 0.019$*

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Homogeneity of variance assumption has been violated ($p < 0.001$). Welch test is used instead of *F* test. Games-Howell *post-hoc* tests were used (Equal variances unassumed). Presence of superscript letters (S, U, G) indicate significant differences between particular countries.

$p = 0.012$). In both Germany ($B = 0.12$, $SE = 0.05$, $p = 0.033$) and Singapore ($B = 0.13$, $SE = 0.04$, $p < 0.001$), higher income participants were more likely to accept the product. In Singapore, males were more likely to accept the product as compared to females ($B = 0.23$, $SE = 0.05$, $p < 0.001$). In the USA, living in a more urbanized environment was associated with higher product acceptance ($B = 0.08$, $SE = 0.04$, $p = 0.049$).

As for diet, flexitarians in all three countries were more accepting of the product as compared to omnivores (Germany: $B = 0.71$, $SE = 0.07$, $p < 0.001$; USA: $B = 0.43$, $SE = 0.07$, $p < 0.001$; Singapore: $B = 0.26$, $SE = 0.06$, $p < 0.001$). Vegetarians in Germany ($B = 0.83$, $SE = 0.13$, $p < 0.001$), and vegans in Germany ($B = 1.06$, $SE = 0.19$, $p < 0.001$) and USA ($B = 0.60$, $SE = 0.23$, $p = 0.007$) were more accepting of the product as compared to omnivores.

Additionally, the consumption frequency of organic (Germany: $B = 0.09$, $SE = 0.03$, $p < 0.001$; USA: $B = 0.09$, $SE = 0.03$, $p = 0.003$; Singapore: $B = 0.07$, $SE = 0.03$, $p = 0.014$) and plant-based egg alternatives (Germany: $B = 0.13$, $SE = 0.03$, $p < 0.001$; USA: $B = 0.17$, $SE = 0.03$, $p < 0.001$; Singapore: $B = 0.13$, $SE = 0.03$, $p < 0.001$) positively predicted acceptance of the product in all three countries. Consumption frequency of normal eggs in USA ($B = 0.05$, $SE = 0.02$, $p = 0.040$) and that of free-range eggs ($B = 0.05$, $SE = 0.02$, $p = 0.019$) in Singapore positively predicted acceptance of the product.

Reasons for product acceptance

A Pearson's chi-square test of contingencies was used to investigate whether the top reasons attracting participants to buy PF egg products differed across countries.[3] The chi-square test was statistically significant, χ^2 (26, $N = 3{,}008$) = 325.70, $p < 0.001$. In Germany, the top three reasons were better animal welfare (22%), curiosity (18.2%) and less use of antibiotics (8.8%). In the USA, the top three reasons were curiosity (18.1%), health (11.6%) and no cholesterol (10.1%). In Singapore, the top three reasons were price (17.1%), health (14.8%) and curiosity (13.5%). Curiosity was a popular reason for all three countries, more so for participants in USA. German participants were mostly drawn to the product due to animal welfare reasons while price was the top reason that attracted Singapore participants to the product (Table 5).

3 Total weighted sample size is slightly different from the total count in Table 5 because the cell counts have been rounded.

Discussion

Understanding who, where, why and when cellular agriculture derived foodstuffs will find willing consumers is crucial for the commercial viability of cellular agriculture and relatedly, its potential to make large-scale social impact. In this section, we discuss the overall consumer acceptance of PF made egg products and the factors that may encourage consumer acceptance. Our results offer insight into the market level enthusiasm for PF made food products, while also illuminating for whom and why PF products will attract interest and adoption. Notably, our paper examined differences between countries, and the different dietary identities and habits that correspond to varying levels of enthusiasm for PF made food products. Our research also offers an overview of the driving reasons consumers see for the adoption of a PF egg product.

Overall acceptance

The results show that there were significant differences between countries on some specific aspects of product acceptance, but not on overall product acceptance. Overall, a substantial proportion of consumers, i.e., between 51 to 61% of participants in all three countries surveyed, were at least willing to try out PF egg products. These figures are comparable to past findings on consumer acceptance of cultivated meat, another cellular agricultural product (see Bryant and Barnett, 2020 for a review). However, compared to a previous study on consumer acceptance of PF cheese, which had an acceptance rate of over 70%, consumer acceptance of PF egg is relatively low (Zollman Thomas and Bryant, 2021).

Given that cellular agricultural products offer common benefits such as food safety and lower environmental footprints, it would be interesting for future studies to explore why there is a difference in consumer acceptance of PF egg as compared to PF cheese. It is possible that consumers are more accepting of PF cheese simply because dairy is the most established PF product category and has already made market inroads in some geographies (Good Food Institute, 2023b). However, there may be other possible explanations such as perceived product novelty or naturalness. Conventional eggs and meat are unprocessed ingredients, whereas conventional cheese already comes across as a processed food product (Monteiro et al., 2018). The idea of cheese being industrially processed may be more familiar and palatable to consumers, as well as the product format,

TABLE 4 Hierarchical regression model showing demographic and dietary variables predicting product acceptance of precision fermentation egg.

	Germany		USA		Singapore	
	B (SE)	*P*	B (SE)	*p*	B (SE)	*p*
Step 1						
Demographic variables						
Age	−0.01 (0.00)***	<0.001	−0.01 (0.00)***	<0.001	−0.00 (0.00)	0.083
Gender (ref = females)	−0.10 (0.07)	0.153	0.09 (0.07)	0.171	0.27 (0.05)***	<0.001
Income	0.18 (0.06)**	0.002	0.07 (0.05)	0.179	0.11 (0.04)**	0.006
Degree of urbanization	0.06 (0.04)	0.161	0.11 (0.04)*	0.011	–	–
Education	−0.04 (0.02)	0.116	0.08 (0.03)**	0.002	−0.01 (0.02)	0.780
R^2	0.045		0.056		0.036	
Adjusted R^2	0.041		0.051		0.032	
F	9.487***		11.837***		9.289***	
Step 2						
Demographic variables						
Age	−0.01 (0.00)***	<0.001	−0.01 (0.00)***	<0.001	−0.01 (0.00)**	0.002
Gender (ref = females)	0.03 (0.07)	0.641	0.10 (0.06)	0.109	0.27 (0.05)***	<0.001
Income	0.14 (0.06)*	0.012	0.08 (0.05)	0.109	0.14 (0.04)***	<0.001
Degree of urbanization	0.03 (0.04)	0.412	0.09 (0.04)*	0.031	–	–
Education	−0.05 (0.02)*	0.027	0.07 (0.02)**	0.002	−0.02 (0.02)	0.474
Current diet (ref = Omnivore)						
Flexitarian	0.78 (0.07)***	<0.001	0.52 (0.07)***	<0.001	0.33 (0.06)***	<0.001
Vegetarian	0.91 (0.13)***	<0.001	0.48 (0.19)*	0.014	0.33 (0.12)**	0.005
Vegan	1.15 (0.18)***	<0.001	0.79 (0.23)***	<0.001	0.47 (0.20)*	0.018
Others	−0.24 (0.27)	0.366	0.16 (0.15)	0.301	0.24 (0.18)	0.175
R^2	0.184		0.111		0.072	
Adjusted R^2	0.177		0.103		0.065	
Δ R^2	0.139		0.055		0.036	
F	24.858***		13.774***		9.663***	
Δ *F*	42.113***		15.343***		9.712***	
Step 3						
Demographic variables						
Age	−0.01 (0.00)***	<0.001	−0.00 (0.00)	0.053	−0.00 (0.00)	0.356
Gender (ref = females)	0.00 (0.07)	0.954	0.02 (0.06)	0.736	0.23 (0.05)***	<0.001
Income	0.12 (0.05)*	0.033	0.03 (0.05)	0.550	0.13 (0.04)***	<0.001
Degree of urbanization	0.04 (0.04)	0.373	0.08 (0.04)*	0.049	–	–
Education	−0.04 (0.02)*	0.032	0.06 (0.02)*	0.012	−0.03 (0.02)	0.137
Current diet (ref = Omnivore)						
Flexitarian	0.71 (0.07)***	<0.001	0.43 (0.07)***	<0.001	0.26 (0.06)***	<0.001
Vegetarian	0.83 (0.13)***	<0.001	0.14 (0.19)	0.480	0.23 (0.12)	0.054
Vegan	1.06 (0.19)***	<0.001	0.60 (0.23)**	0.007	0.29 (0.20)	0.143
Others	−0.24 (0.26)	0.357	0.07 (0.15)	0.628	0.26 (0.17)	0.135
Frequency of consumption						
Organic eggs	0.09 (0.03)***	<0.001	0.09 (0.03)**	0.003	0.07 (0.03)*	0.014
Free range eggs	0.01 (0.03)	0.735	0.03 (0.03)	0.200	0.05 (0.02)*	0.019
Normal eggs	0.02 (0.03)	0.499	0.05 (0.02)*	0.040	0.01 (0.02)	0.614

(Continued)

TABLE 4 (Continued)

	Germany		USA		Singapore	
	B (SE)	*P*	B (SE)	*p*	B (SE)	*p*
Plant-based egg alternative	0.13 (0.03)***	<0.001	0.17 (0.03)***	<0.001	0.13 (0.03)***	<0.001
R^2	0.216		0.186		0.136	
Adjusted R^2	0.206		0.175		0.125	
Δ R^2	0.032		0.075		0.064	
F	20.927***		17.327***		12.980***	
Δ *F*	10.041***		22.619***		18.272***	

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Degree of urbanization was not included in the regression analyses for Singapore.

TABLE 5 Reasons that will attract participant to buy precision fermentation egg product across countries for the weighted sample.

	Germany *N*=1,001 *n* (%)	USA *N*=1,001 *n* (%)	Singapore *N*=1,004 *n* (%)
Reasons that will attract one to buy product			
Less use of antibiotics	88 (8.8%)	29 (2.9%)	39 (3.9%)
Better animal welfare	221 (22.0%)	93 (9.3%)	77 (7.6%)
Great taste	57 (5.6%)	97 (9.7%)	74 (7.4%)
Less environmental impact	66 (6.6%)	81 (8.1%)	76 (7.6%)
Curiosity	182 (18.2%)	181 (18.1%)	136 (13.5%)
Fits with a vegan diet	47 (4.7%)	22 (2.2%)	40 (4.0%)
Use of new technology	16 (1.6%)	39 (3.9%)	32 (3.1%)
No cholesterol	75 (7.5%)	101 (10.1%)	111 (11.0%)
Protein content	28 (2.8%)	74 (7.4%)	57 (5.7%)
Price	62 (6.2%)	93 (9.3%)	171 (17.1%)
Health	69 (6.9%)	116 (11.6%)	149 (14.8%)
No egg allergens	16 (1.6%)	22 (2.2%)	13 (1.3%)
Others (e.g., Safety, etc)	4 (0.4%)	8 (0.8%)	11 (1.1%)
None/not interested	71 (7.1%)	45 (4.5%)	18 (1.8%)

unlike a PF egg product which would not be sold as individual, shelled eggs. In evaluating the naturalness of a food, consumers consider not only the content of the end-product, but also the processes it has undergone as well (Rozin, 2006). Food that has been processed by traditional (i.e., older) means may be perceived as more natural than food that has been processed by recently developed technologies (Etale and Siegrist, 2021). Compared to PF cheese, PF eggs may be perceived as a more novel or unnatural product that can potentially induce food neophobia. Finally, people may simply perceive the production of dairy to be more objectionable than that of eggs, finding more reasons to replace dairy products in their diets. Consumers' stated reasons for being attracted to a PF egg product and how these precipitate differences in acceptance compared to other cellular agriculture products will be examined in the following sections.

Demographics

A number of demographic characteristics have been hypothesized to predict attitudes and behaviors with regard to APs. However, extant findings on the impact of demographic variables on consumer acceptance of APs are mixed (Nguyen et al., 2022). While some studies show that demographics influence consumer acceptance of APs (e.g., Gómez-Luciano et al., 2019; Orkusz et al., 2020), others report that the impact of demographics is insignificant (e.g., de Boer et al., 2013; Birch et al., 2019; Barton et al., 2020).

In our results, older and higher educated participants predicted lower acceptance of the product in Germany while higher educated participants in the U.S. were more likely to accept the product. In both Germany and Singapore, higher income participants were more likely to accept the product. In Singapore, males were more likely to accept the product as compared to females. In the U.S., living in a more urbanized environment was associated with higher product acceptance.

In step 2 of our hierarchical regression, age was a statistically significant predictor of enthusiasm for the product across countries, but our largely diffuse results mirror wider findings around AP acceptance, with variable and/or weak connections seen between demographics such as gender or degree of urbanization and enthusiasm, while generally showing a prevailing trend that younger and more educated consumers are more likely to accept

APs (de Boer et al., 2013; Birch et al., 2019; Gómez-Luciano et al., 2019; Siegrist and Hartmann, 2019; Wilks et al., 2019).

In our results, only one demographic factor consistently predicted acceptance of PF egg products across regression steps and in at least two countries – income. That is, an increase in income was related to higher acceptance of PF egg products. This finding is supported by Tucker (2014), which showed that higher income positively affected consumers' perception of APs. One possible explanation for the income-acceptance relationship may be perceived affordability. That is, the higher one's income, the more affordable a novel food product such as PF egg is perceived to be. Price – and by extension, affordability – was found to play an important role in motivating AP consumption and in moderating consumer demand for APs (Slade, 2018). In a recent study, the Good Food Institute (2022) reported price to be a barrier to the consumption of APs: e.g., "consumers ranked price as the second-most important factor (behind taste) to encourage or discourage them from purchasing a plant-based product" (Good Food Institute, 2022, p. 5).

A second possible explanation for the relationship between higher income and higher acceptance of PF egg is that individuals with higher-income backgrounds have been associated with higher novelty-seeking scores (Lahti et al., 2006). As novelty seeking is one of the factors that can drive AP consumption (Tan et al., 2016; Apostolidis and McLeay, 2019; Mancini and Antonioli, 2019), we posit that higher-income individuals are more likely to engage in novelty-seeking behavior, which in turn drives their willingness to consume PF egg. This is an area that merits further research.

Dietary identities

As public awareness around the health, environmental and ethical consequences of unmoderated animal product consumption and production have risen, a greater share of consumers are changing their dietary identities to reflect this concern (Sanchez-Sabate and Sabaté, 2019).

Given that the development of cellular agriculture was born from a willingness to directly address concerns around unhealthy, unsustainable and degrading food practices (Mattick, 2018), examining how those pursuing alternative diets evaluate the appeal of cellular agriculture has been a natural focus for much of the research community when examining the societal adoption of novel foodstuffs (Stephens et al., 2018). Our research too examines the relationship between dietary identities and a willingness to consume a PF made egg product, with some findings corroborating existing research around the acceptance of cellular agriculture foods (Bryant et al., 2020; Zollman Thomas and Bryant, 2021), and some indicating notable differences in the dynamics toward attitudes surrounding a PF produced egg substitute. The predictive power of these dietary identities stands in contrast to our demographic data, which gently reiterated findings around age while also pointing to a moderate relationship between income and product enthusiasm.

Flexitarians

Our work provides insight into the volume of consumers electing to pursue alternative diets currently, as well as the relationship between these choices and an openness to embrace PF made foodstuffs. Our data replicates many existing surveys' findings regarding the level of vegans, vegetarians and flexitarians in Germany, Singapore, and the USA (Ho, 2020; Dagevos, 2021), with, once again particularly notable levels of flexitarians in Germany (forming a higher overall percentage of society than omnivores), as well as displaying the highest levels of veganism and vegetarianism among our sampled countries. While apparently closer to Europe in terms of culinary traditions and social traditions, Germany and Singapore were seen to be closer in level of animal product abstainers than the USA, showing a smaller percentage of its population to identify as flexitarians, vegetarians or vegans than Singapore or Germany.

In accordance with previous findings, our results showed strong predictive power to be associated with diet on the embrace of a novel food product (Szejda et al., 2021; Zollman Thomas and Bryant, 2021). Of all surveyed traits, diet had the strongest influence on acceptance, exhibiting both a stronger and more statistically significant relationship with PF egg acceptance than other examined demographic traits such as age, gender, income and education. Specifically, flexitarians were significantly more likely, in every country, to see themselves as future consumers of PF produced egg products than omnivores.

This finding, viewed in conjunction with the recorded burgeoning of the flexitarian movement (Dagevos, 2021), suggests that as more of society begins to acknowledge a need, and develops a readiness to reduce consumption of animal products, a wider pool of consumers are likely to be drawn to the fruits of cellular agriculture, in particular, PF made food. The noted capacity of new technologies to prompt wider societal norm changes (Verbeek, 2011) may well create a compounding effect, of awareness and necessary change arising from the introduction of PF made egg, particularly in an area such as egg production, which currently draws comparatively less public attention for its impact on the environment or the welfare of chickens than mammalian-based agriculture (Alonso et al., 2020).

Vegetarians and vegans

While an anticipated advantage of cultivated meat and PF food categories is its capacity to move beyond audiences typically served by plant-based animal substitute products (Silva and Semprebon, 2021), understanding the acceptance and enthusiasm of this consumer grouping, namely vegans and vegetarians, provides insight both into the foothold to be gained in this dedicated section of the market, and to understand whether and how new products will widen the range of consumers substituting away from animal products.

Existing research shows cultivated meat and, to a lesser extent, PF made dairy products, to be of strongest interest to those who currently consume meat and dairy respectively, with flexitarians having generally displayed the highest willingness to adopt products made through cellular agriculture (Bryant, 2020; Zollman Thomas and Bryant, 2021). Vegan consumers are notable in displaying more ambivalence toward products created through these new technologies than vegetarians or flexitarians (Baum et al., 2022), with potential reasons being the animal cell origins of cultivated meat, an aversion to unnaturalness or their success in having already removed meat and dairy from their diets (Faccio and Nai Fovino, 2019). Indeed, within groups reducing animal product consumption, enthusiasm for cultivated meat or PF is typically lowest among vegans, higher among vegetarians and again higher among flexitarians (Bryant et al., 2019).

Our findings regarding the acceptability of a PF produced egg products are highly notable given the reversal of this trend, with our regression showing vegans to display the highest levels of enthusiasm for such a product, with flexitarians showing relatively lower enthusiasm than vegans and vegetarians. These relationships hold in all of the observed countries. The reversal of this relationship suggests that consumers of PF made egg may share relatively more similarities with the consumers of plant-based APs, which are relatively more favored by vegans (Smart Protein Project, 2021), than the anticipated consumers of cultivated meat, or even PF made dairy products.

Numerous factors could explain this, related to the relationship of both flexitarians and vegans to eggs and existing egg alternatives, and their perceptions of other cellular agriculture technologies. Relationships that warrant further research is whether for some vegans, egg may be a more difficult product to find suitable replacements for, or similarly, the attitude of flexitarians toward eggs. As mentioned, eggs are products that are not viewed as carrying an equivalent moral burden to that of the beef or dairy industry (Alonso et al., 2020), with these attitudes potentially explaining why relatively more flexitarians are less interested by the use of novel technologies to replace eggs. Flexitarians often cite environmental reasons as the grounds for their dietary choices (Sanchez-Sabate et al., 2019), and just as these groups may hold a diminished association of chicken eggs to the most deplorable animal-welfare conditions, chicken eggs too are likely not associated with the dire environmental consequences that beef and dairy are (Hartmann et al., 2021). Finally, it may simply be that for many vegans who are relatively less enthusiastic about the use of cell culturing or the genetic engineering of microorganisms, applying PF technology in this setting is simply more acceptable than the animal biopsies necessary to begin the cell-culturing process, or the identical replication of dairy cow DNA in microorganism hosts, than the replication of egg proteins in microorganisms.

Consumption habits

While it is necessary to view the acceptance of PF egg through a social and political lens, considering the attitudes and heuristics driving acceptance of new food technology, the focuses of consumer scientists - consumer habits and purchasing patterns - are also highly relevant when seeking to understand the anticipated adoption and purchase decisions of consumers, and certainly more neglected when examining acceptance of novel foods, given scant primary data. While some studies have investigated the role of dietary behaviors in predicting attitudes to plant-based products (Kester, 2023) or cultivated meat (Malek and Umberger, 2021), little research thus far has examined consumers' granular dietary behavior, such as the choices and degree of consumption of conventional products and existing substitutes, with focus on how these relate to novel food products, especially PF made products. When noting that the impact of cellular agriculture depends not on the volume of consumers likely to adopt it, rather the volume of consumers' purchases of animal products that are eschewed given its introduction, this focus is overdue in the field.

In this way, our observations about the relative differences in egg consumption behavior between countries, and their observed relationship to PF acceptance, should be of especial note, not just for those seeking to understand the mechanics of a societal shift toward cellular agriculture, but also for those looking to understand how markets and product categories will be impacted by PF's emergence.

Our results show significant differences in the frequency of different categories of egg consumption across countries, with German respondents reporting a higher level of organic, and free-range egg consumption, while consuming lower levels of 'normal eggs' (i.e., eggs with no higher-welfare certifications). While Singaporeans reported the highest levels of 'normal' egg consumption, they reported the lowest levels of organic and free-range egg consumption, with Americans falling, respectively, between the other two countries in terms of consumption levels. These values demonstrate immediately the differences between German, American and Singaporean attitudes toward egg consumption, and the behavior already exhibited that reflect context, assessments and priorities within their "egg-buying" environments.

We found that the frequency of consuming plant-based eggs was positively related to the acceptance of PF produced egg products. Prior research has found high levels of consumer dissatisfaction with existing vegan substitutes for animal products (Rondoni et al., 2021). As such, it is likely that consumers who consume vegan egg substitutes remain on the lookout for better alternative proteins, which can more holistically satisfy their varied demands for nutrition, safety, and sensory appeal on top of being cruelty-free and planet-friendly, hence their observed enthusiasm for a PF egg product.

Similarly, a strong positive relationship between organic egg consumption and consumer acceptance of PF produced egg products suggests that those who do consume eggs, but exert relatively more effort to consume higher welfare standard eggs are more likely to embrace PF produced egg products. This fits with Heidemann's work into cultivated meat acceptance which linked the emergence of cultivated meat with support for organic animal rearing (Heidemann et al., 2020). Seeing the direction and strength of these relationships in all countries suggests that consumer behavior acts as a relatively robust means to anticipate the types of consumer segments and habits that PF egg consumption will correspond to, in juxtaposition to factors such as age, gender and education.

Reasons

Beyond an examination of the demographics and dietary trends cellular agriculture will likely synchronize with, an examination of the reasons why consumers are attracted to PF made food is a necessary undertaking. Existing research shows animal product reduction to be driven by both personal motives, such as health and taste, and prosocial concerns, including environment and animal welfare (Armstrong Soule and Sekhon, 2019), with the adoption of meat replacement products majorly derived from environmental factors, with lower impact derived from health messaging (Silva and Semprebon, 2021; Ye and Mattila, 2021). The examination of the reasons consumers find compelling poses additional insights into why people are likely to make the shift from traditional animal-based foods to PF products, offering help to identify the consumer priorities and opportunities that may facilitate a shifting of societal protein consumption.

The present study revealed that the driving forces behind the trial of PF egg products differed among the three countries. German participants were primarily motivated by their perception of the products' benefits for animal welfare and reduced use of antibiotics. By

contrast, Americans were drawn to the health benefits, such as a lack of cholesterol of PF egg products. Singaporean participants were found to be influenced by a combination of health and price considerations.

Interestingly, across all three countries, participants indicated that they are open to consuming PF egg products because of their curiosity. It is reasonable to argue that as PF products are currently one of the most innovative alternatives to animal-made products, many potential consumers are attracted to this novel food as a result of their curiosity and novelty-seeking tendency. In fact, this is consistent with the prior finding that novelty seeking has been shown to be a key driver for promoting the consumption of APs (Apostolidis and McLeay, 2019; Mancini and Antonioli, 2019). It would be worthwhile for future research to examine the sustained interest or acceptance of PF products after first-time consumers have tried the products to satisfy their curiosity.

Another notable finding is that among the three countries, particularly within Singapore and the USA, that respondents listed health-related reasons (i.e., use of less antibiotics, no cholesterol) for explaining their openness to PF egg products, suggesting the potential for overlap both with personal and prosocial reasons for a PF egg product. This aligns with the evidence that health concerns or health consciousness act as drivers or barriers to accept plant-based meat alternatives (e.g., Siegrist and Hartmann, 2019) and cultivated meat (e.g., Verbeke et al., 2015; Adámek et al., 2018; Grasso et al., 2019). The current finding echoes prior research that health is a highly relevant factor that prospective consumers deliberate about when considering the acceptability of APs, including new PF products.

As previously mentioned, interest in a PF egg product was moderately lower than interest for a PF dairy product, of which consumers perceived significant environmental benefits over standard dairy products, with a comparable perception of health qualities (Zollman Thomas and Bryant, 2021). The absence of environmental reasons provided by consumers in our survey could explain some of the difference seen between PF product categories.

Conclusion

The findings of this research suggest that PF made egg products are likely to find a willing market, with a substantial proportion (51–61%) of consumers in the USA, Germany and Singapore at least willing to try out such a product. While there were significant differences between countries on some aspects of product acceptance, overall acceptance of the product was comparable across the countries. The strongest predictor of acceptance was dietary identity, with flexitarians being significantly more likely to accept the product than omnivores in all countries, with vegetarians and vegans displaying still higher enthusiasm, in contrast to major findings around cultivated meat and PF dairy acceptance. Other predictors of acceptance included degree of urbanization in the USA and age in Germany. Consumption habits also significantly predicted acceptance, with those consuming higher welfare standard eggs, and those consuming plant-based egg substitutes being more likely to accept the product. Reasons for acceptance included health, animal welfare, price and curiosity.

Future research is warranted to examine two major areas: deeper insight into the nature and mechanics of consumer acceptance of PF products, and, how this can be altered by experiences, framing and targeting. A more detailed examination of the differences between countries is warranted, as well as the impact of demographics, dietary identity and consumption habits on acceptance, especially when sampling the product, or being exposed to it in a supermarket, restaurant or food-service environment. Our research did not control the scepticism or trust that consumers placed in the product performance and product claims. Future research should examine the extent to which consumers believe product claims, how this shapes expectations of the product, and how these factors interact with willingness to try and buy. In this respect, the efficacy of different strategies to overcome scepticism, neophobia and reluctance would be of particular value for those looking to market PF based products to consumers, or, equally, discourage their uptake.

Further fruitful avenues of research may include direct examinations of the differences in consumer acceptance of PF egg compared to PF cheese or other products, and to examine the levels of sustained interest or acceptance of PF products after initial curiosity is satisfied, and when, if ever, consumers would consider completely substituting away from conventional eggs. Finally, research should investigate the reasons why vegans and vegetarians are comparatively more likely to accept PF egg than flexitarians, and how this could inform the marketing and positioning of different PF products.

The findings of this research and the outcomes of future research may well prove instrumental in normalizing the consumption of PF produced egg products, in turn altering how we eat. In parallel, the uptake of PF products may well "denormalise" the vast, industrialized processes behind contemporary animal product consumption, in turn altering how they live.

Data availability statement

The datasets presented in this article are not readily available because data is not readily available to outside researchers. Requests to access the datasets should be directed to oscar@formo.bio.

Ethics statement

The studies involving human participants were reviewed and approved by SMU Institutional Review Board. The participants provided their informed consent online to participate in this study.

Author contributions

OZT: conceptualization, translation, and data collection. OZT, MC, and AL: research design, survey instrument design, and analysis. TF, MC, SN, and OZT: data processing and data analysis. All authors contributed to the drafting and editing of the manuscript and approved the submitted version.

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Conflict of interest

OZT was employed by Formo Bio GmbH.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1209533/full#supplementary-material

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