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Consumer acceptance of cultured, plant-based, 3D-printed meat and fish alternatives

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A R T I C L E I N F O

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A B S T R A C T

Novel food technologies, such as three-dimensional (3D) food printing and cellular agriculture, offer many opportunities in the field of meat and fish production, such as texture variety, food waste reduction, animal welfare, and personalized nutrition. Nevertheless, they still face resistance from consumers. Thus far, conventional meat and fish have yet to be compared simultaneously with other food alternatives. Therefore, we conducted a study to analyze acceptance of these alternatives among Swiss consumers in terms of perceived healthiness, willingness to buy, willingness to eat, and perceived environmental friendliness. In doing so, conventional meat and fish were compared on these four acceptance measures with 3D-printed plant-based, cultured, 3D-printed cultured, plant-based, and 3D-printed byproduct meat and fish alternatives. The results suggest that the plant-based alternatives perform best, whereas the 3D-printed byproduct meat or fish alternatives perform worst on all acceptance measures assessed. Moreover, perceptions of healthiness and environmental friendliness of the meat or fish alternatives appear to be the most important predictors of willingness to eat. These results indicate that future focus should be placed on communicating the health- and environment-related benefits of 3D food printing and cellular agriculture to facilitate their adoption.

Introduction

With the growing world population (Arango et al., 2023), the demand for animal proteins is increasing, inducing the meat industry to increase production (Bonny et al., 2017). Meanwhile, environmental problems from food production, such as deforestation and overfishing of the oceans, continue, and calls to reduce meat consumption are growing louder (Hubbard, 2023; Schiermeier, 2019; Westhoek et al., 2014). Furthermore, meat consumers experience a moral dilemma due to their concern that animals have to lose their lives for their consumption (Hartmann and Siegrist, 2020). Notably, despite these negative aspects associated with meat consumption, only a minority of consumers seem willing to replace meat with alternative protein products (Hartmann and Siegrist, 2017). In the present study, we examined how consumers perceive various meat and fish alternatives. We focused not only on plant-based (Boukid, 2021; Rubio et al., 2020) and cultured meat (Post, 2012, 2014) but also included products based on three-dimensional (3D) food printing technology (Mahmoud et al., 2021; Scheele et al., 2020, 2022, 2023). Most previous studies focused on meat only, whereas the present study included fish replacements as well. We were interested in determining whether 3D food printing is evaluated differently compared with cultured meat and plant-based meat substitutes.

Plant-based meat alternatives based on legumes, cereals, and fungi are gaining popularity among certain consumer groups (Starowicz et al., 2022). These meat alternatives aim to resemble conventional meat in taste and texture to meet consumer needs (Michel et al., 2021; Starowicz et al., 2022). Nevertheless, they often fail to replicate the complex structure of conventional meat. A novel technology that aims to solve this problem is 3D food printing. A 3D printer enables the customization of food into various shapes and the incorporation of a diverse selection of ingredients to better respond to consumer preferences and replicate intricate food structures (L. Zhong et al., 2023). Furthermore, 3D food printing has the potential to imitate fish-muscle-structures (C. Zhong et al., 2023) and produce fish analogs with a similar nutritional value to the original (Nowacka et al., 2023). In addition, 3D printing might help reduce food waste and increase the sustainability of meat products (Lupton and Turner, 2017; Manstan and McSweeney, 2020). Not only the conventional but also the so-called cultured meat grown in a

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bioreactor through the muscle stem cells of an animal could be used with a 3D printing technology (Lupton and Turner, 2018; Post, 2014; Zhang et al., 2020). Improved animal welfare and less use of water, land, and feed grain compared with established agriculture might be some potential benefits of cultured meat (Chriki and Hocquette, 2020; Hong et al., 2021). Fish from cellular agriculture promises to be able to save wild fish species that cannot be farmed through aquaculture, to be free of antibiotics, toxins, and microplastics, and also contribute to animal welfare by eliminating the need for fish (Carneiro et al., 2022).

Through the combination of 3D food printing and meat cultivation, highly structured meat like steak might be produced (Gaydhane et al., 2018), and nutritional content along with a realistic texture could be achieved (Handral et al., 2022), which might lead to higher consumer acceptance (Handral et al., 2022). To sum up, 3D printing technology offers advantages and flexibility as textures and shapes can be fabricated in cultured meat production (Ben-Arye and Levenberg, 2019; Bhat et al., 2015; Handral et al., 2022; Tuomisto and Teixeira De Mattos, 2011).

Similarly, 3D food printing technology could also be used to produce premium meat cut analogs based on animal byproducts (Dong et al., 2023; Ramachandraiah, 2021). The processing of meat byproducts is already well-known in sausages production. Through 3D food printing, they could be additionally processed into slurries that can be used in the layering process. The meat paste is extruded and glued together with normal food-grade enzymes (Bonny et al., 2017). This allows meat byproducts, such as raw meat and offcuts, powdered meat, collagen derivates, blood plasma protein, tallow, and lard, to gain value (Bonny et al., 2017). Fish processing generates several byproducts, including backbones, thorns, skins, and fins, which can serve as rich sources of nutrients and bioactive compounds (Al Khawli et al., 2020; Nawaz et al., 2020). In sum, this processing might reduce food waste and contribute to the sustainability of food systems. However, technological solutions alone are not enough to reduce meat consumption; consumer perceptions must also be taken into account (Siegrist and Hartmann, 2023).

Consumer acceptance of alternative proteins

Consumers are often reluctant to try foods based on novel food technologies and are influenced by factors such as perceived naturalness and trust in the food industry (Siegrist and Hartmann, 2020a). In fact, 3D food printing technology was not evaluated positively in previous research. In various studies, the participants expressed concerns about potential health threats of the 3D-printed food (Lupton and Turner, 2018b), particularly due to its perceived artificiality (Lupton and Turner, 2017). A potential obstacle to the widespread acceptance of this technology may arise from people's limited understanding of 3D food printing, as the majority of consumers are unfamiliar with 3D-printed food and harbor skepticism toward it. This negative attitude could be slightly improved through information about improved flavor, convenience, healthiness, and naturalness of these products (Brunner et al., 2018). For 3D-printed cultured meat products, a majority of the participants were worried about the degree of processing and considered them as unnatural, not nutritious, lacking taste, and potentially harmful (Lupton and Turner, 2018b). In general, cultured meat is often associated with unnaturalness (Guan et al., 2021; Lewisch and Riefler, 2023; Pakseresht et al., 2022; Siegrist and Hartmann, 2020b). This feeling can also evoke disgust toward cultured meat which leads to its rejection (Siddiqui et al., 2022; Siegrist et al., 2018). In addition, consumers view the safety and nutritional value of cultured meat with skepticism (Hansen et al., 2021; Pakseresht et al., 2022). Food neophobia is a further obstacle in terms of consumer acceptance (Brunner et al., 2018; Lee et al., 2021). This should be less of a problem with plant-based products, as they have been marketed for some time and have thus already gained recognition among consumers (Onwezen et al., 2021; Profeta et al., 2021; Szenderák et al., 2022). Nevertheless, the perception of sensory properties has a significant impact as well (Safdar et al., 2022). One of the barriers to the acceptance of plant-based meat alternatives is its flavor, which is perceived to be inferior to conventional meat (Michel et al., 2021; Wang et al., 2022). Therefore, plant-based meat alternatives should resemble conventional meat as close as possible (Michel et al., 2021a). The same concerns about taste have also been found with regard to cultured meat (Guan et al., 2021; Siddiqui et al., 2022).

Overall, consumers' perceptions determine the success of new products in the marketplace (Cattaneo et al., 2019); hence, it is essential to take consumers' views into account from the beginning (Siegrist and Hartmann, 2020a). However, consumer acceptance seems to be the biggest challenge next to technological feasibility regarding the implementation of cultured meat or fish (Siegrist and Hartmann, 2020a), as well as in the case of 3D food printing (Lupton and Turner, 2018b). For this reason, a question arises as to which factors influence the acceptance of 3D-printed foods and cell-cultivated products among consumers.

Study objectives

Previous studies have investigated several important factors influencing the perception and acceptance of novel food products, such as perceived naturalness, feelings of disgust evoked by a novel food technology, and trust in the food industry (Marcu et al., 2015; Siegrist and Hartmann, 2020a; Siegrist and Sütterlin, 2017; Verbeke et al., 2015). However, many studies have focused on cultured meat only (Mancini and Antonioli, 2019; Verbeke et al., 2015; Weinrich et al., 2020) or compared it with conventional meat and plant-based meat alternatives (Slade, 2018). To the best of our knowledge, studies that compare several alternatives for meat and fish simultaneously are lacking. Moreover, little research has been done on fish alternatives (Estell et al., 2021; Gorman et al., 2023; Kazir and Livney, 2021).

For five meat and fish alternatives (3D-printed plant-based meat and fish, cultured meat and fish, 3D-printed cultured meat and fish, plant-based meat and fish alternative, and 3D-printed byproducts of meat and fish), four different acceptance measures (perceived healthiness, willingness to buy, willingness to eat, and perceived eco-friendliness) were compared. Second, conventional steak and salmon were compared with the alternative products to identify the differences in perceived healthiness and willingness to eat. Third, we examined which factors predict acceptance of meat and fish alternatives, such as curtailment behavior in the food domain and trust in the food industry.

Methods

The data collection took place via an online survey in the German language in August 2022 in the German-speaking part of Switzerland. The participants' consumption of meat and fish, trust in the food industry, curtailment behavior in the food domain, meat and fish attachment, and sociodemographic variables (gender, age, and education) were measured. The participants were randomly assigned to one of five conditions (between-subject design) and evaluated one of five different meat and fish alternatives based on four acceptance measures.

Participants

The study participants were recruited from the online panel of a commercial provider of sampling services (Bilendi & Respondi AG) and were rewarded with a monetary incentive for their participation. Quota samples were used, with the quota variables gender (50 % women) and age (an equal number of participants for each of the five age groups: 20–29, 30–39, 40–49, 50–59, 60–70). The participants who did not complete the survey ($n = 64$), who undercut the minimum survey duration of half of the median time ($n = 96$), and who responded several times ($n = 4$) were excluded. The vegetarians and vegans ($n = 6$) were removed from the statistical analysis to ensure they did not influence the results regarding the dislike of meat. This resulted in 1012 respondents, with 513 women (50.7 %) and 494 (48.8 %) men. Three participants chose a diverse gender (0.3 %) and two (0.2 %) did not specify. The mean age was 45 years (*SD* = 15, range 20–69 years). The participants' educational levels were divided into three categories: low, 10 % (*n* = 101, primary and lower secondary school), middle, 64 % (*n* = 648, secondary school, vocational education, and senior high school), and high, 26 % (*n* = 263, higher vocational education, university and above). The survey asked how often the participants consumed meat, meat alternatives, fish, and seafood. The responses were given on a six-point scale with the following options: "several times per day," "once per day," "several times per week," "several times per month," "several times per year," and "rarely/never." Meat alternatives were consumed mostly rarely or never (40.8 %, *n* = 413), whereas fish was consumed mostly several times per month (39 %, *n* = 395). A total of 18.7 % (*n* = 189) of the participants indicated that they consume fish rarely or never.

The study was approved by the Ethics Commission of ETH Zurich (EK 2022-N-124).

Measures

Acceptance of meat and fish alternatives

First, the participants had to rate a conventional steak and salmon on their perceived healthiness and willingness to eat on a scale from 0 (unhealthy/for sure not) to 100 (healthy/for sure). This part was followed by the randomized assessment of one of five meat and fish alternatives in a between-subject design: 3D-printed plant-based meat/fish (1), cultured meat/fish (2), 3D-printed cultured meat/fish (3), plant-based meat/fish alternative (4), and 3D-printed byproducts of meat/fish (5).

The participants always rated the same alternative for meat and fish. The description for each alternative constantly started the same way: "Meat/fish production is associated with immense environmental impacts. A more environmentally friendly alternative is…." The text was presented together with a picture of 3D-printed plant-based meat or a cultured fish, respectively, using the same image for every meat and fish alternative. The randomly assigned meat and fish alternatives had to be rated on the acceptance measures of perceived healthiness, willingness to buy, willingness to eat, and perceived eco-friendliness, with a slider ranging from 0 to 100. It should be noted that due to technical reasons, two participants had missing values on the acceptance measure willingness to buy. The descriptions of the meat and fish alternatives are shown in Tables 1 and 2.

Trust in stakeholders in the food sector

The participants had to provide their level of agreement regarding four items that measure trust in the stakeholders in the food sector (Siegrist and Hartmann, 2020b) using the following items: "I trust the food industry," "You can rely on governmental controls in the food sector," "I trust food retailers," and "I trust food scientists." The statements were rated on a six-point Likert scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). The internal consistency was high (α = 0.91), and an average trust score was calculated. The mean value in the sample was 3.79 (*SD* = 1.05).

Curtailment behavior in the food domain

Ecological behavior in food purchasing was measured by the curtailment behavior scale in the food domain (Sütterlin et al., 2011). The participants had to indicate on a six-point Likert scale how often they perform the five activities regarding the perceived environmental impact of food: "buy regional foods," "buy seasonal fruits and vegetables," "avoid buying foods flown in," "avoid buying foods from distant countries," and "reduce meat consumption." The response options ranged from 1 (*never*) to 6 (*always*). For this scale, the Cronbach's alpha was 0.79, and the observed mean value was 3.93 (*SD* = 0.85).

Meat and fish attachment

The Meat Attachment Questionnaire (MAQ; Graça et al., 2015) measures the bond toward meat consumption. The MAQ consists of 16 items, such as "To eat meat is one of the good pleasures in life" or "To eat meat is disrespectful toward life and the environment." The internal consistency was high (α = 0.88). An adapted version was developed with a focus on fish instead of meat. The resulting Fish Attachment Questionnaire contains five items: "Fish is irreplaceable in my diet," "I love meals with fish," "To eat fish is disrespectful toward life and the environment," "I would feel fine with a fishless diet," and "If I was forced to stop eating fish, I would feel sad." This questionnaire also showed high internal consistency (α = 0.83). The mean value for meat attachment was 3.11 (*SD* = 0.72) and 2.86 (*SD* = 1.04) for fish attachment.

Table 1
Description of meat alternatives.

	Introductory Sentence
	Meat production is associated with immense environmental impacts.
3D-printed plant-based	A more environmentally friendly alternative is 3D-printed steak. A base mass consisting of powdered rice, pea protein, algae fiber, and beet juice for coloring is produced. Then, the base mass is printed into a steak shape using a 3D printer.
Cultured meat	A more environmentally friendly alternative is cultured meat. Cultured meat is produced by tissue propagation. In this process, cells are obtained from the muscle tissue of cows. These cells are multiplied and developed into muscle fibers.
3D-printed cultured meat	A more environmentally friendly alternative is 3D-printed cultured meat. Cultured meat is produced by tissue propagation. In this process, cells are obtained from the muscle tissue of cows. These cells are multiplied and developed into muscle fibers. The mass of the cultured meat is then printed into steak form using a 3D printer.
Plant-based	A more environmentally friendly alternative is a vegan meat substitute. The meat substitute consists mainly of pea protein and does not contain soy or gluten.
3D-printed byproduct meat	Meat byproducts from meat production should also be utilized. In addition to the production of charcuterie or sausages, a meat paste consisting of such meat byproducts can be printed in steak form using a 3D food printer.

Table 2
Description of fish alternatives.

	Introductory Sentence
	Fish production is associated with immense environmental impacts.
3D-printed plant-based	A more environmentally friendly alternative is 3D-printed salmon. The basic mass consists of pea proteins, algae extracts, plant fibers, and vegetable oils. This is used to create a kind of dough, which is then heated and printed as a salmon fillet using a 3D printer.
Cultured fish	A more environmentally friendly alternative is cultured salmon. Cultured salmon is produced by tissue propagation. In this process, cells are obtained from the muscle tissue of salmon. These cells are propagated and developed into muscle fibers.
3D-printed cultured fish	A more environmentally friendly alternative is 3D-printed cultured salmon. Cultured salmon is produced by tissue propagation. In this process, cells are obtained from the muscle tissue of salmon. These cells are multiplied and developed into muscle fibers. The fish mass from cultured salmon is then printed as a salmon fillet using a 3D printer.
Plant-based	A more environmentally friendly alternative is a vegan salmon substitute. The salmon substitute consists of carrots that have been marinated for several hours in a mixture of oil, vinegar, seaweed, and liquid smoke. Thus, they have absorbed the marinade and come close to the taste and texture of salmon.
3D-printed byproduct fish	Fish byproducts generated during fish production should also be recycled. A fish paste consisting of such fish byproducts can be printed as a salmon fillet using a 3D food printer.

Statistical analysis

All statistical analyses were performed using the SPSS Statistics software package version 28 (SPSS Inc., Chicago, IL). To determine the differences between the alternatives, a one-way analysis of variance (ANOVA) followed by post-hoc tests (Tukey HSD) were carried out between all alternatives for each acceptance measure. The mean values and 95 % confidence intervals of conventional steak and salmon on the acceptance measures of perceived healthiness and willingness to eat were compared with each alternative product. Furthermore, multiple linear regressions were performed to evaluate the influence of socio-demographic variables and other assessed variables on the dependent variable willingness to eat the five meat and fish alternatives. Socio-demographic variables, trust in the food sector, curtailment behavior in the food domain, and meat and fish attachment, respectively, were included in the regression model. Furthermore, perceived healthiness and eco-friendliness were added to the model to distinguish between those variables directly related to the respective meat or fish alternative.

Results

Acceptance of meat alternatives

Based on the results of the ANOVA, perceived healthiness exhibited a statistically significant difference between the five meat alternatives $F(4,1007) = 11.60$, $p < 0.001$. The lowest healthiness perceptions were observed for the 3D-printed byproduct and 3D-printed cultured meat, which did not differ from each other (see Fig. 1 and Table A1). In comparison, perceived healthiness was rated higher for the cultured meat and 3D-printed plant-based alternative. The highest healthiness perception was observed for the plant-based alternative.

For willingness to buy, statistically significant differences between the meat alternatives were revealed $F(4,1007) = 3.24$, $p < 0.05$. The 3D-printed byproduct and 3D-printed cultured meat had the lowest indicated willingness to buy. Willingness to buy was highest for the cultured meat and plant-based alternative but did not show a statistically significant difference from the 3D-printed plant-based alternative (see Table A1).

Willingness to eat the meat alternatives exhibited statistically significant difference $F(4,1007) = 3.84$, $p = .004$. The lowest willingness to eat was observed for the 3D-printed byproduct and 3D-printed cultured meat, which did not differ from the willingness to eat the 3D-printed plant-based alternative (see Fig. 2 and Table A1). The highest willingness to eat was observed for the plant-based alternative and cultured meat.

Perceived eco-friendliness differed statistically significantly between the meat alternatives $F(4,1007) = 3.81$, $p = .004$ The 3D-printed byproduct meat was perceived as the least eco-friendly, whereas the plant-based alternative was discerned to be the most environmentally friendly (see Table A1).

Acceptance of fish alternatives

Statistically significant differences were observed between the five alternative fish products in terms of perceived healthiness $F(4,1007) = 6.69$, $p < 0.001$. The 3D-printed byproduct and 3D-printed cultured fish were perceived as the least healthy. Perceived healthiness was highest for the cultured fish, plant-based, and 3D-printed plant-based alternatives, which did not differ from each other (see Fig. 1 and Table A2).

Willingness to buy varied statistically significantly between the fish alternatives $F(4,1005) = 2.40$, $p < 0.05$. The lowest willingness to buy was observed for the 3D-printed byproduct and 3D-printed cultured fish. Higher values were observed for the cultured fish, plant-based, and 3D-printed plant-based alternative, which did not differ from each other (see Table A2).

Furthermore, statistically significant differences were noted between the fish alternatives $F(4,1007) = 2.85$, $p < 0.05$ in terms of willingness to eat. The willingness to eat 3D-printed byproduct fish was the lowest. Higher values were observed for the 3D-printed cultured fish and 3D-printed plant-based alternative. The willingness to eat the plant-based alternative and cultured fish were the highest values (see Fig. 2 and Table A2).

Statistically significant differences between the perceived eco-friendliness of fish alternatives were observed $F(4,1007) = 2.39$, $p = 0.05$. The lowest level of perceived eco-friendliness was noted for the 3D-printed byproduct. The level of perceived eco-friendliness was highest for the plant-based alternative, followed by cultured fish, 3D-printed plant-based alternative, and 3D-printed cultured fish, which did not differ from each other (see Table A2).

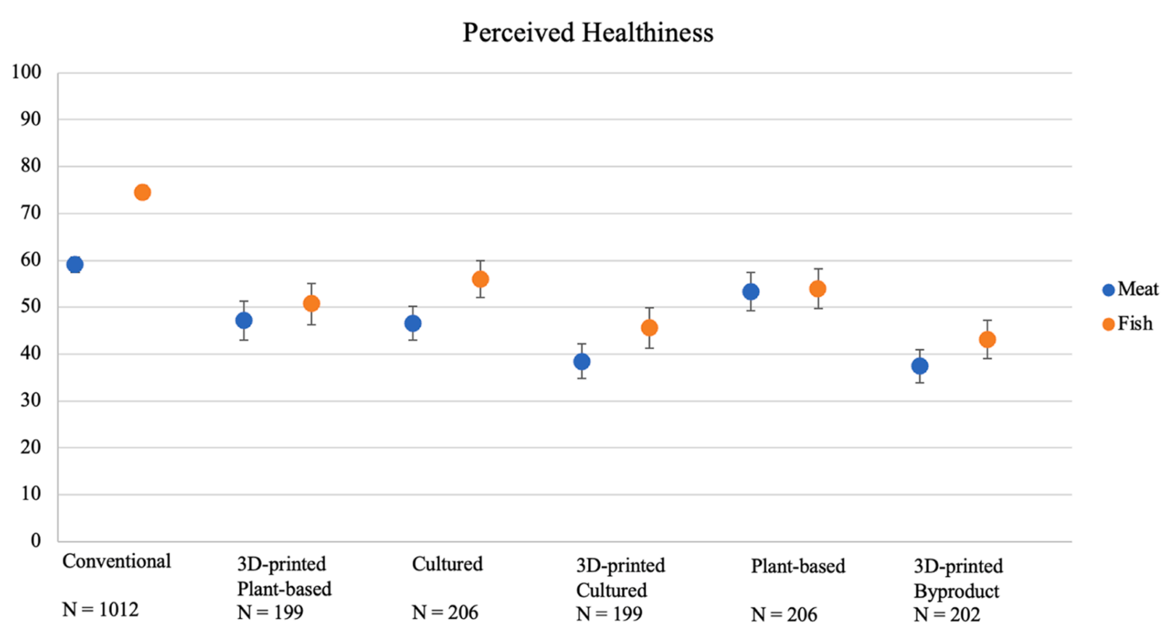

Fig. 1. Perceived healthiness of meat and fish alternatives compared with conventional steak and salmon.
Note. Means and 95 % CI level.

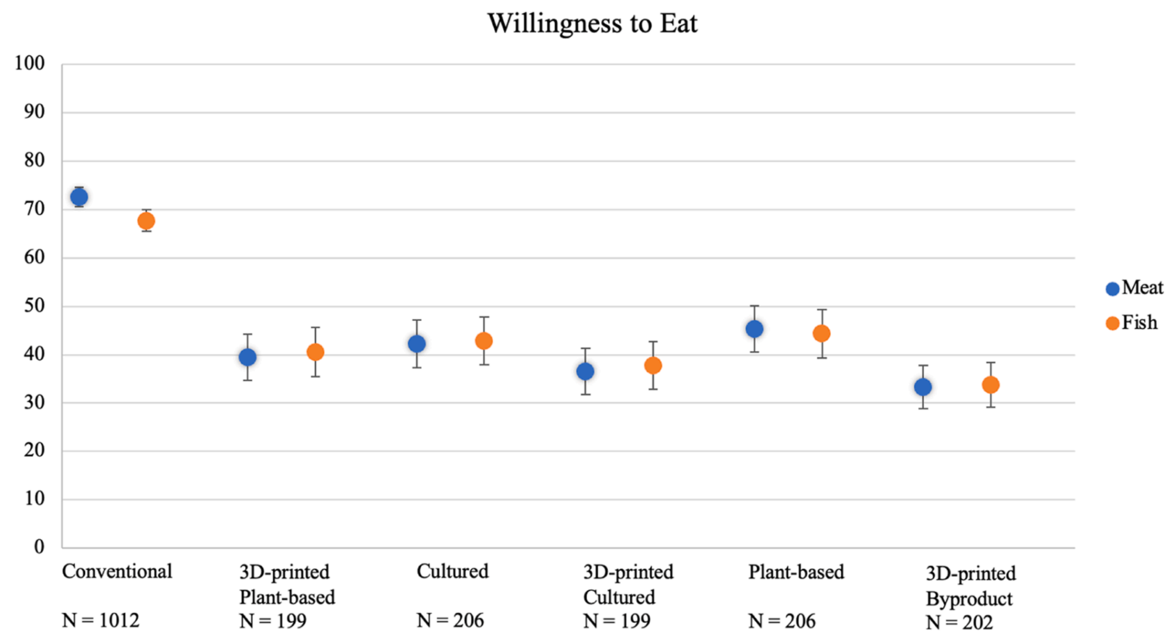

Fig. 2. Willingness to eat meat and fish alternatives compared with conventional steak and salmon.
Note. Means and 95 % CI level.

Conventional steak and salmon in comparison with alternatives

Fig. 1 shows the mean values and 95 % confidence intervals for the perceived healthiness of conventional steak and salmon in comparison with each alternative. Conventional steak and salmon were judged by all participants ($N = 1012$), whereas the other products were evaluated by a subgroup of participants randomly assigned to the condition (N = 199–206). All paired t-test comparisons of the perceived healthiness between the conventional steak and the five meat alternatives were statistically significantly different, except for the plant-based alternative. The comparisons between the conventional salmon and its alternatives were all statistically significant.

Fig. 2 shows the mean values and 95 % confidence intervals for the willingness to eat conventional steak and salmon in comparison with each alternative. All paired t-test comparisons between willingness to eat conventional steak and alternative products were statistically significantly different. For salmon, all comparisons were statistically significantly different as well.

Factors influencing the willingness to eat meat alternatives

For each product, the impact of sociodemographic variables, trust, curtailment behavior, and meat attachment on the willingness to eat was examined by regression analyses. All regression analyses predicting willingness to eat meat alternatives were significant. The regression models explained between 43 % and 59 % of variance. For all meat alternatives, the perceived healthiness and environmental friendliness positively predicted the willingness to eat the product. In addition, people with lower education and lower curtailment behavior were more willing to eat the 3D-printed plant-based alternative. Males and younger participants were more willing to eat cultured meat. Meat attachment and age had a negative influence on willingness to eat the plant-based meat alternative (see Table 3).

Table 3
Results of five multiple linear regression analyses with the acceptance measure “willingness to eat meat alternatives” as a dependent variable.

	3D-printed Plant-based $N = 198$		Cultured $N = 204$		3D-printed Cultured $N = 199$		Plant-based $N = 205$		3D-printed Byproduct $N = 201$	
	B	*ß*	**B**	*ß*	**B**	*ß*	**B**	*ß*	**B**	*ß*
Intercept	43.15		−1.33		−3.22		54.15		−6.38	
Gender	1.79	.03	9.65	.14**	5.79	.08	0.63	.01	2.24	.04
Age	0.05	.02	−0.45	−0.18***	−0.08	−0.03	−0.34	−0.15**	−0.17	−0.08
Education	−2.23	−0.11*	−0.36	−0.02	−0.79	−0.04	0.94	.05	1.02	.05
Trust	0.87	.03	−0.13	−0.00	−1.32	−0.04	−2.16	−0.07	0.45	.01
Curtailment	−5.16	−0.14*	1.18	.03	1.67	.04	0.15	.00	0.39	.01
Meat Attachment	−4.81	−0.11	2.79	.06	0.96	.02	−9.66	−0.19***	0.09	.00
Perceived Healthiness	0.56	.49***	0.80	.59***	0.58	.45***	0.38	.33***	0.62	.49***
Perceived Eco-Friendliness	0.21	.19*	0.25	.20***	0.40	.36***	0.39	.34***	0.39	.32***

Note. Gender coding: 0 = female, 1 = male.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
3D-printed plant-based: adj. $R^2 = 0.43$; $F(8,189) = 19.60$; $p < 0.001$.
Cultured meat: adj. $R^2 = 0.59$; $F(8,195) = 38.10$; $p < 0.001$.
3D-printed cultured meat: adj. $R^2 = 0.54$; $F(8,190) = 30.42$; $p = < 0.001$.
Plant-based alternative: adj. $R^2 = 0.53$; $F(8,196) = 29.64$, $p < 0.001$.
3D-printed byproduct meat: adj. $R^2 = 0.55$; $F(8,192) = 31.32$, $p < 0.001$.

Factors influencing the willingness to eat fish alternatives

Similarly, all multiple regression analyses predicting willingness to eat fish alternatives were significant. The regression models explained between 47 % and 62 % of variance. Among all the fish alternatives, perceived healthiness, environmental friendliness, and fish attachment were important for predicting willingness to eat. Furthermore, males showed more willingness to eat the 3D-printed byproduct, while younger participants were more willing to eat the cultured fish. In addition, trust in the food industry had a positive influence on the willingness to eat the 3D-printed byproduct (see Table 4).

Discussion

The aim of the present study was to investigate consumers' acceptance of meat and fish alternatives in terms of their perceived healthiness, willingness to eat, willingness to buy, and perceived eco-friendliness. In addition, the products were compared with the perceived healthiness and willingness to eat conventional steak and salmon to elicit their potential and ascertain which alternative can achieve the best or even similar perceptions among consumers. Moreover, we examined whether sociodemographic factors and other variables, such as trust in the food sector, curtailment behavior in the food domain, meat or fish attachment, and perceived healthiness and eco-friendliness, can predict the acceptance of meat and fish alternatives.

Our research showed that the acceptance of meat and fish alternatives was rather low. Among all the meat alternatives tested, the plant-based alternative was rated best, whereas the 3D-printed byproduct meat was rated worst across all acceptance measures. One possible explanation could be that plant-based meat alternatives are familiar to consumers, not only among vegetarians but also among people who want to reduce their meat consumption (Starowicz et al., 2022). Familiarity has been shown to be a key driver of consumer acceptance of alternative proteins (Onwezen et al., 2021; Szenderák et al., 2022), which might have led to a higher appreciation of the plant-based alternative. Furthermore, meat byproducts are already used and frequently consumed in sausage production. However, its combination through 3D food printing is novel, which is probably why this technology was met with rejection. Interestingly, its environmental friendliness was also perceived badly, even though byproduct utilization is supposed to be sustainable through the use of side streams of food production (Bonny et al., 2017; Siegrist and Hartmann, 2023). Although meat byproducts could increase in value in terms of sustainability through 3D printing (Ramachandraiah, 2021), consumers are probably not aware of this advantage. Furthermore, consumers may feel disgusted by the processing of meat byproducts. This is consistent with the concern expressed in previous studies about 3D-printed food being overly processed (Lupton and Turner, 2017, 2018a).

Similarly, among fish alternatives, the 3D-printed fish based on byproduct utilization was rated worst on all acceptance measures, while the participants perceived cultured fish as the healthiest alternative and were more willing to buy it. On the acceptability measures of willingness to eat and perceived environmental friendliness, the plant-based fish alternative received the best rating. Still, conventional steak and salmon were perceived as much better in terms of healthiness and willingness to eat in comparison with all meat and fish alternatives.

Factors influencing willingness to eat meat and fish alternatives

Perceived healthiness and environmental friendliness of the respective meat or fish alternative were the most important predictors of willingness to eat. Product-specific attributes were more important compared with sociodemographic or person-related factors.

Male and younger participants were more willing to eat cultured meat than female and older participants. These findings are in line with previous research on cultured meat showing higher acceptance from men and younger people (Bryant and Barnett, 2020; Mancini and Antonioli, 2019). Age was negatively associated with willingness to eat the plant-based meat alternative, which is consistent with a previous finding that the younger generations consume more meat alternatives (Szenderák et al., 2022). Age was not associated with willingness to eat a plant-based fish alternative; however, when it comes to fish alternatives, age was only a significant predictor for cultured fish, showing again that younger people were more willing to eat it.

In addition, the participants with higher meat attachment were less willing to eat the plant-based meat alternative. For the other meat alternatives, meat attachment was not associated with willingness to eat.

A different picture emerged when it came to fish alternatives. Higher fish attachment led to a higher willingness to eat all fish alternatives but the 3D-printed plant-based alternative. This finding suggests that fish alternatives seem to be an option for consumers for whom fish is an important part of their diet.

Table 4
Results of five multiple linear regression analyses with the acceptance measure "willingness to eat fish alternatives" as a dependent variable.

	3D-printed Plant-based $N = 198$		Cultured $N = 204$		3D-printed Cultured $N = 199$		Plant-based $N = 205$		3D-printed Byproduct $N = 201$	
	B	*ß*	**B**	*ß*	**B**	*ß*	**B**	*ß*	**B**	*ß*
Intercept	2.10		−21.83		−37.40		−26.13		−36.10	
Gender	0.65	.01	5.79	.09	6.43	.09	1.96	.03	6.52	.11*
Age	0.01	.00	−0.24	−0.10*	0.02	.01	−0.09	−0.04	−0.17	−0.07
Education	0.52	.02	0.84	.04	−0.35	−0.02	1.11	.05	1.81	.09
Trust	−0.42	−0.01	−2.73	−0.08	1.20	.03	−1.51	−0.05	3.68	.11*
Curtailment	−3.44	−0.09	2.02	.05	2.72	.06	2.69	.06	1.36	.03
Fish Attachment	3.18	.10	6.16	.18***	5.91	.17***	5.30	.14**	3.72	.12*
Perceived Healthiness	0.67	.59***	0.54	.43***	0.55	.48***	0.57	.47***	0.55	.48***
Perceived Eco-Friendliness	0.14	.12	0.49	.40***	0.35	.32***	0.34	.28***	0.28	.24***

Note. Gender coding: 0 = female, 1 = male.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
3D-printed plant-based: adj. $R^2 = 0.47$; $F(8,189) = 22.65$; $p < 0.001$.
Cultured fish: adj. $R^2 = 0.60$; $F(8,195) = 39.51$; $p < 0.001$.
3D-printed cultured fish: adj. $R^2 = 0.59$; $F(8,190) = 37.19$; $p = < 0.001$.
Plant-based alternative: adj. $R^2 = 0.47$; $F(8,196) = 23.68$, $p < 0.001$.
3D-printed byproduct fish: adj. $R^2 = 0.50$; $F(8,192) = 26.38$, $p < 0.001$.

Implications and further studies

The results of this study show that 3D-printed meat and fish made of byproducts were rated worst on all acceptance measures, whereas the plant-based alternatives were more appreciated.

Compared with conventional steak and salmon, the meat and fish alternatives were perceived poorly in terms of perceived healthiness and willingness to eat. Therefore, it might be important to consider similarities with conventional meat and fish in terms of various sensory and nutritional properties when introducing alternatives. In addition, it is important to consider the other benefits of cultured meat or fish, such as less food waste, application of 3D food printing for people with chewing difficulties, personalized nutrition (L. Zhong et al., 2023), and animal welfare (Chriki et al., 2022). Future studies may examine whether providing additional information about meat and fish alternatives results in a more positive perception.

The most important predictors for willingness to eat the meat and fish alternatives were perceived healthiness and eco-friendliness. These findings suggest that the alternatives not only need to be good for the environment but healthy as well. However, this will be a challenge because the nutritional value of some meat alternatives is inferior compared with conventional meat, and, for others, it remains unknown (Siegrist and Hartmann, 2023). Consumers perceive cultured meat mostly as unhealthy and assume its taste to be inferior compared with conventional meat (Bryant and Barnett, 2020; Mancini and Antonioli, 2019; Siegrist and Hartmann, 2023). In fact, in the case of cultured meat, there are fundamental aspects, such as the nutritional profile, texture, and flavor, that need to be worked on (Guan et al., 2021). Perceived environmental friendliness is an important predictor for the acceptance of meat alternatives. Plant-based meat analogs mostly have a lower environmental impact compared with meat, but for novel technologies like cultured meat, the impact is still uncertain. The results of the present research suggest that different marketing techniques for meat and fish should be used.

Given the relationship between fish attachment and the willingness to eat fish alternatives, the introduction of 3D-printed plant-based and cultured fish products should be targeted toward people who already buy and regularly consume conventional fish. For meat substitutes, the most promising target group seems to be flexitarians who have a moderate level of meat consumption (Dagevos, 2021; Estell et al., 2021; Michel et al., 2021; Szenderák et al., 2022).

Limitations

Some limitations of this study must be addressed. First, since the participants were only shown images of meat and fish alternatives as part of an online survey, it was not possible to evaluate the taste and texture of the presented food. Therefore, the evaluations, especially regarding willingness to eat the 3D-printed and cultured alternatives, were only hypothetical, as they are currently unavailable or still being developed. Second, steak and salmon were assessed; therefore, the type of meat or fish could have influenced consumer perception. However, salmon is the most consumed fish species in Switzerland (Federal Office for Agriculture, 2019) and also the most frequently imitated through fish analogs (Nowacka et al., 2023). Finally, the online study was conducted in the German-speaking part of Switzerland and may therefore not be representative of other parts of Switzerland or other countries. This assumption is linked to the fact that attitudes toward cultured meat (Bryant and Sanctorum, 2021; Mancini and Antonioli, 2019; Siegrist and Hartmann, 2020b; Verbeke et al., 2015) and plant-based meat alternatives (Bryant et al., 2019; Gómez-Luciano et al., 2019) differ among cultures: Muslim populations, for example, appear doubtful of cultured meat's halal status, whereas Buddhist populations expressed a higher willingness to adapt the technology for animal welfare reasons compared to other motivations (e.g., nutritional aspects) (Chong et al., 2023). Moreover, a study conducted in 10 nations showed that there were substantial differences in the perception of cultured meat. France had the lowest acceptance of cultured meat; consumers in that country perceived it as completely unnatural and felt utterly disgusted by it. In contrast, relatively high levels of acceptance were found in Mexico, South Africa, and England (Siegrist and Hartmann, 2020b). Due to differences in culinary tradition, culture, and religion, we also expect heterogeneity in the perception of 3D-printed meat and fish alternatives among countries. To gain a better understanding of consumer attitudes toward these alternatives, cultural comparisons should be made.

Conclusion

The aim of this study was to investigate which meat and fish alternatives are more likely to be accepted and to compare them with their conventional equivalents. Furthermore, factors that can predict willingness to eat these alternatives were investigated.

Compared with conventional meat and fish, the alternatives produced by 3D printing and cell cultivation still have a long way to go. Despite claimed advantages, including higher environmental friendliness, animal welfare, and healthiness (Bonny et al., 2017), consumer perception of 3D-printed and cultured alternatives is worse compared with conventional products. According to consumer perception, plant-based meat and fish alternatives already seem to be fairly well established. Furthermore, we found evidence that a major challenge will be to make the benefits of meat byproducts using a novel technology such as 3D food printing palatable to consumers.

Ethics approval

The study was approved by the Ethics Committee of ETH Zurich (EK 2022-N-124).

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Ethical statement for research paper

Ethical approval for the involvement of human subjects in this study was granted by the ethic commission of the ETH Zürich. Reference number EK 2022-N-124 (July 2022). Participants gave informed consent via the statement "I hereby agree to participate in this study. The information provided as part of the study will be stored separately from my personal data and will be used purely for scientific purposes" where an affirmative reply was required to enter the survey. They were able to withdraw from the survey at any time without giving a reason. The study was explained to consumers in the online questionnaire. They were informed that all data will be anonymized and only reported aggregate.

CRediT authorship contribution statement

Madeleine Lanz: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Christina Hartmann:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Paul Egan:** Conceptualization, Writing – review & editing. **Michael Siegrist:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Appendix

Tables A.1–A.4

Table A.1
Means and standard deviations of acceptance measures of meat alternatives.

	Acceptance Measure Perceived Healthiness	Willingness to Buy	Willingness to Eat	Perceived Eco-Friendliness
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
3D-printed plant-based (*N* = 199)	47.12 (29.64)[a]	34.45 (32.61)[a,b]	39.46 (33.87)[a,b]	45.39 (30.75)[a,b]
Cultured meat (*N* = 206)	46.59 (26.57)[a]	39.56 (33.99)[a]	42.21 (35.90)[a,b]	44.36 (28.42)[a,b]
3D-printed cultured meat (*N* = 199)	38.49 (26.72)[b]	32.52 (32.33)[a,b]	36.55 (34.40)[a,b]	44.15 (30.80)[a,b]
Plant-based alternative (*N* = 206)	53.34 (29.84)[a]	38.39 (33.48)[a,b]	45.34 (34.95)[a]	49.31 (30.44)[a]
3D-printed byproduct meat (*N* = 202)	37.39 (25.75)[b]	29.70 (29.30)[b]	33.27 (32.36)[b]	38.06 (26.98)[b]

Note. Different letters within each column indicate significant ($p < 0.05$) differences based on the Tukey HSD post-hoc test.

Table A.2
Means and standard deviations of acceptance measures of fish alternatives.

	Acceptance Measure Perceived Healthiness	Willingness to Buy	Willingness to Eat	Perceived Eco-Friendliness
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
3D-printed plant-based (*N* = 199)	50.67 (31.57)[a]	36.09 (34.50)[a,b]	40.51 (36.32)[a,b]	46.28 (31.08)[a,b]
Cultured fish (*N* = 206)	56.03 (28.44)[a]	39.74 (34.43)[a]	42.88 (35.76)[a,b]	47.40 (29.04)[a,b]
3D-printed cultured fish (*N* = 199)	45.56 (30.76)[b]	34.35 (34.00)[a,b]	37.76 (35.07)[a,b]	45.83 (32.03)[a,b]
Plant-based alternative (*N* = 206)	53.96 (30.67)[a]	38.50 (35.39)[a,b]	44.32 (36.76)[a]	50.17 (30.60)[a]
3D-printed byproduct fish (*N* = 202)	43.09 (29.39)[b]	30.42 (30.66)[b]	33.77 (33.82)[b]	41.13 (28.76)[b]

Note. Different letters within each column indicate significant ($p < 0.05$) differences based on the Tukey HSD post-hoc test.

Table A.3
Results of five multiple linear regression analyses predicting willingness to eat meat alternatives as dependent variables.

	3D-printed Plant-based *N* = 198		Cultured *N* = 204		3D-printed Cultured *N* = 199		Plant-based *N* = 205		3D-printed Byproduct *N* = 201	
Intercept	43.15 [14.24; 72.06]		–1.33 [–27.35; 24.69]		–3.22 [–33.11; 26.66]		54.15 [23.24; 85.06]		–6.38 [–33.59; 20.83]	
Gender	1.79 [–4.87; 8.45]	.03	9.65 [3.31;15.99]	.14**	5.79 [–0.99; 12.58]	.08	0.63 [–5.57; 6.84]	.01	2.24 [–3.39; 7.88]	.04
Age	0.05 [–0.21; 0.31]	.02	–0.45 [–0.69; –0.21]	–.18***	–0.08 [–0.32; 0.16]	–.03	–0.34 [–0.57; –0.11]	–.15**	–0.17 [–0.39; 0.05]	–.08
Education	–2.23 [–4.42; –0.04]	–.11*	–0.36 [–2.51; 1.79]	–.02	–0.79 [–2.77; 1.18]	–.04	0.94 [–1.07; 2.95]	.05	1.02 [–0.94; 2.97]	.05
Trust	0.87 [–2.62; 4.36]	.03	–0.13 [–3.26; 2.99]	–.00	–1.32 [–4.63; 2.00]	–.04	–2.16 [–5.50; 1.18]	–.07	0.45 [–2.68; 3.58]	.01
Curtailment	–5.16 [–9.38; –0.94]	–.14*	1.18 [–2.89; 5.24]	.03	1.67 [–2.79; 6.12]	.04	0.15 [–3.78; 4.07]	.00	0.39 [–3.43; 4.21]	.01
Meat Attachment	–4.81 [–10.03; 0.40]	–.11	2.79 [–1.84; 7.41]	.06	0.96 [–4.12; 6.04]	.02	–9.66 [–15.12; –4.20]	–.19***	0.09 [–4.51; 4.69]	.00
Perceived Healthiness	0.56 [0.39; 0.73]	.49***	0.80 [0.64; 0.95]	.59***	0.58 [0.42; 0.75]	.45***	0.38 [0.21; 0.56]	.33***	0.62 [0.47; 0.77]	.49***
Perceived Eco-Friendliness	0.21 [0.05;0.38]	.19*	0.25 [0.11; 0.39]	.20***	0.40 [0.26; 0.54]	.36***	0.39 [0.22; 0.56]	.34***	0.39 [0.25; 0.53]	.32***

Note. Shown are beta (CI) and the p-value. Gender coding: 0 = female, 1 = male.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
3D-printed plant-based adj. $R^2 = 0.43$.
Cultured meat adj. $R^2 = 0.59$.
3D-printed cultured meat adj. $R^2 = 0.54$.
Plant-based alternative adj. $R^2 = 0.53$.
3D-printed byproduct meat adj. $R^2 = 0.55$.

Table A.4
Results of five multiple linear regression analyses predicting willingness to eat fish alternatives as dependent variables.

	3D-printed Plant-based N = 198		Cultured N = 204		3D-printed Cultured N = 199		Plant-based N = 205		3D-printed Byproduct N = 201	
Intercept	2.10 [–23.00; 27.21]		–21.83 [–45.06; 1.40]		–37.40 [–62.29; –12.52]		–26.13 [–56.04; 3.78]		–36.10 [–61.43; –10.77]	
Gender	0.65 [–6.22; 7.52]	.01	5.79 [–0.51; 12.08]	.09	6.43 [–0.04; 12.89]	.09	1.96 [–4.85; 8.77]	.03	6.52 [0.41; 12.64]	.11*
Age	0.01 [–0.27; 0.28]	.00	–.24 [–0.47; –0.00]	–.10*	0.02 [–0.22; 0.25]	.01	–0.09 [–0.34; 0.17]	–.04	–0.17 [–0.42; 0.08]	–.07
Education	0.52 [–1.73; 2.77]	.02	0.84 [–1.30; 2.97]	.04	–0.35 [–2.23; 1.53]	–.02	1.11 [–1.13; 3.35]	.05	1.81 [–0.30; 3.92]	.09
Trust	–0.42 [–3.94; 3.10]	–.01	–2.73 [–5.81; 0.35]	–.08	1.20 [–1.96; 4.35]	.03	–1.51 [–5.15; 2.12]	–.05	3.68 [0.22; 7.14]	.11*
Curtailment	–3.44 [–7.70; 0.82]	–.09	2.02 [–1.91; 5.95]	.05	2.72 [–1.44; 6.88]	.06	2.69 [–1.73; 7.11]	.06	1.36 [–2.81; 5.52]	.03
Fish Attachment	3.18 [–0.39; 6.75]	.10	6.16 [2.88; 9.43]	.18***	5.91 [2.48; 9.34]	.17***	5.30 [1.31; 9.29]	.14**	3.72 [0.42; 7.02]	.12*
Perceived Healthiness	0.67 [0.51; 0.84]	.59***	0.54 [0.40; 0.68]	.43***	0.55 [0.40; 0.69]	.48***	0.57 [0.38; 0.75]	.47***	0.55 [0.41; 0.70]	.48***
Perceived Eco-Friendliness	0.14 [–0.03; 0.31]	.12	0.49 [0.35; 0.63]	.40***	0.35 [0.21; 0.49]	.32***	0.34 [0.15; 0.53]	.28***	0.28 [0.13; 0.43]	.24***

Note. Shown are beta (CI) and the p-value. Gender coding: 0 = female, 1 = male.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
3D-printed plant-based adj. $R^2 = 0.47$.
Cultured fish adj. $R^2 = 0.60$.
3D-printed cultured fish adj. $R^2 = 0.59$.
Plant-based alternative adj. $R^2 = 0.47$.
3D-printed byproduct fish adj. $R^2 = 0.50$.

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