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Title: **How do you want your steak? Attitudes of European consumers towards 3D printed meat.**

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Tasks: Chaloupkova P (writing, data collecting, data analysis, study conceptualization), Kokoskova T* (writing, data analysis, study conceptualization), Ceacero Herrador F (data analysis), Durand C, Onakuse S (data collection, study conceptualization), Kokoska L (writing, study conceptualization).

Highlights

- Interest in 3D printed food was higher than in 3D printed meat among European consumers.
- Sensory and socio-economic factors heavily influence conventional meat consumption.
- Promoting 3D printed meat requires highlighting environmental benefits and good taste.

Abstract

This study examines European consumer attitudes towards reducing meat consumption due to environmental and health concerns, exploring the potential of cultured meat for 3D printing as a healthier and environmentally friendly alternative. The research analysed parameters predicting consumer attitudes and behaviour toward 3D printed meat, focusing on conventional meat consumption habits, attitudes, purchase behaviour, and sensory factors. The study involved a survey of 571 consumers across France, the Czech Republic, and Ireland. The questionnaire was divided into four categories: conventional meat consumption habits, factors affecting meat consumption, knowledge about 3D printed products, and willingness to try 3D printed food and meat. Path analysis was used to explore the effects of various factors on meat consumption habits and interest in 3D printed meat. The results indicated that while respondents demonstrated interest in trying 3D printed food, their interest in 3D printed meat was significantly lower. Furthermore, the findings showed that sensory factors, such as taste, aroma, and colour, along with socio-economic factors, significantly influenced conventional meat consumption habits. Conversely, interest in 3D printed meat was primarily influenced by taste, economic value, environmental impact, religious reasons, together with conventional meat consumption habits. A pivotal role in the promotion of 3D printed meat will be occupied by a well-designed communication strategy that highlights its positive environmental impacts. Concurrently, from the perspective of producers, it will be crucial to focus on the final taste of the 3D printed meat, with the ultimate price of the meat also being a significant consideration.

Introduction

Meat and meat products continue to serve as the primary source of protein for the world's population and meat consumption is expected to increase globally by 12% in 2029 (OECD, 2023). Nevertheless, changes in consumer preferences and attitudes towards meat consumption with regards to its impact on human health, the environment, animal welfare and global greenhouse gas (GHG) emissions, remain among the main factors influencing the development and dynamics of global meat markets (OECD-FAO, 2020). Although, the prediction of an increase in meat consumption also applies to European countries, recent studies have shown that a significant part of European consumers are willing to reduce meat consumption due to the impact of meat production on the environment and health related concerns (Hielkema & Lund, 2021; Ueland, Rødbotten, & Varela, 2022). Excessive consumption of meat and processed meat products, together with other lifestyle factors, has been associated with

overconsumption of total energy and fat, resulting in obesity and an increased risk of chronic diseases (e.g. cardiovascular disease and type 2 diabetes, colorectal cancer) (Salter, 2018). Therefore, the WHO currently recommends eating lean meat or removing visible fat from meat as part of a balanced and healthy diet that reduces the amount of total fat intake (WHO, 2023). Large-scale intensive livestock production systems have been under scrutiny for issues such as deforestation, biodiversity loss, animal welfare concerns, food safety risks and an overall negative impact on the climate (van Wagenberg et al., 2017). It is estimated that up to 57% of total GHG emissions comes from animal food and livestock feed production (Xu et al., 2021). In response, the European Green Deal and Farm to Fork Strategy are currently being devoted to making food systems more sustainable and reducing the environmental impact of livestock farming (Eurostat, 2020).

One of the suggested alternative to satisfy the demand for meat through conventional beef production, because of its impact on the environment and health, is laboratory-grown meat (cultured meat). Laboratory grown meat is produced by culturing animal cells *in vitro* using tissue engineering (Lupton, 2017). Currently, most efforts are focused on culturing cells from the tissues of most common livestock species with the aim to create meat imitations with the equivalent taste, texture, appearance, and nutritional value of conventional meat products (Tiberius, Borning, & Seeler, 2019). In the USA and Europe, there are currently about 50 start-ups focused on the production of cultured meat, primarily beef, pork and chicken (Treich, 2021; Rubio et al., 2020). Although, experts have highlighted the many benefits of cultured meat production, however, the level of consumer acceptance is still unclear, while the demand potential needs to be determined (Manstan & McSweeney, 2020).

An innovative three-dimensional (3D) food printing technology using computer-aided design software working with a digital production machine and containers filled with edible matter (e.g. puree, liquids) has recently been introduced for the manufacture of certain food products such as candies, desserts, and pizza (Lupton & Turner, 2018). This approach allows customising the nutrient composition of the product and direct printing of nutrient-dense foods that meet recommended daily requirements, or personalised food to accommodate intolerances, allergies and other nutrition-related challenges (Manstan & McSweeney, 2020; Severini, Derossi, & Azzollini, 2016; Tran, 2016). In addition, the colours, flavours, shapes, sizes, and textures of the food product can be customized to different consumer requirements, thereby improving the eating experience and overall consumer satisfaction (Liu, Yang, Bhandari, Meng, & Prakash, 2020; Sun, Zhou, Yan, Huang, & Lin, 2018). In addition, this technology makes it possible to transform food waste and alternative nutrition sources (e.g., algae, insects, damaged

fruits and vegetables) into attractive food products (e.g., unique shapes/design) or fine-textured foods to address, for instance, chewing and swallowing difficulties (Lupton & Turner, 2018; Manstan & McSweeney, 2020; Severini, Azzollini, Alenzio, & Derossi, 2018).

Recent research has explored the potential use of cultured meat as an ingredient for 3D printing, with the assumption that the technology has the potential to be both healthy and environmentally friendly. A technology for constructing a steak-like tissue from three types of bovine cell fibres (muscle, fat, and vessel) was recently presented (Kang et. al., 2021). Previous studies have highlighted several potential benefits of 3D printed meat, such as improved nutritional value (e.g. fat reduction), control of health risks (transmission of diseases from animal production and meat processing), animal welfare (reduced number of animals required in systems and slaughtered), and addressing intensive large-scale livestock-related environmental impact issues (e.g. deforestation, land degradation, water pollution and desertification) arising from current conventional animal meat production practices (Brunner, Delley, & Denkel, 2018; Lupton & Turner, 2018). It is also important to mention the negative aspects that consumers perceive as barriers to their interest in 3D meat products. Disgust, safety, and hygiene are among the main concerns of consumers about using a printer to produce food (Lupton & Turner, 2018; Manstan, Chandler, & McSweeney, 2021). Therefore, the attitude of future customers towards the consumption of 3D printed meat will play a crucial role in the successful introduction of this new technology to the market.

Previous studies have focused on consumer acceptance of 3D printed food products (Caulier, Doets, & Noort, 2020; Lupton & Turner, 2018; Manstan, Chandler, & McSweeney, 2021; Lee et al, 2021, Roos et al., 2022); however, the awareness about 3D printed food varies significantly across studies, ranging from relatively low (Brunner, Delley, & Denkel, 2018) to high (Mantihal, Prakash, & Bhandari, 2019). Additionally, products such as pizza, pasta, and sweets may be more easily accepted by consumer than 3D printed meat products like sausages and burgers (Brunner et al., 2018; Lupton & Turner, 2018; Manstan et al., 2021). A crucial aspect related to consumers' attitudes towards 3D printed food is the trust in the information provided about the product quality and its benefits related to health, and more recently, environmental impact. At the same time, the degree of customization required, the state of development, and the suitability of food in 3D printing technology also play a role in the consumer acceptance of 3D printed food (Caulier et al., 2020). Predictors related to the positive attitude towards 3D printed food include consumers' convenience orientation (preference for convenient and short meal preparation), being fun to use, and willingness to consume new food. Conversely, food and technology neophobia, and concerns about the safety of printed food were

the highly associated with negative attitudes (Brunner et al., 2018; Lupton & Turner, 2018). The key aspects influencing the consumers' acceptance of printed food are related to the food composition, appearance, and sensory qualities such as taste and texture (Lupton & Turner, 2018). Regarding the effects of socio-demographic characteristics of consumers on their attitudes to 3D printed food, previous studies have shown different trends. For example, Brunner et al. (2018) confirmed that gender was significantly related to positive attitudes towards 3D printed food, with men being more positive than women. In contrast, Manstan et al., (2021) reported that no gender differences were found, but older participants did not accept 3D printed food as readily as younger participants. Additionally, there was no difference in attitudes toward 3D food printing based on education (Brunner et al., 2018; Manstan et al., 2021; Mantihal et al., 2019). Although some previous studies have dealt with the identification of perceptions and attitudes towards 3D printed foods in general, there is still a lack of information on the willingness to accept 3D printed meat.

Therefore, this study focuses on the analysis of consumer attitudes towards the consumption of 3D printed meat, particularly in the form of steak-like tissue. In general, steak is perceived as more festive, healthy, and tasty compared to the other meat products (Michel, 2021). Since 3D printed steak technology is still in the development phase, this study focused on analysing parameters that could predict potential consumer attitudes and behaviour towards such products. Conventional meat consumption habits, attitudes, purchase behaviour, and sensory factors influencing meat consumption habits were explored for different consumer groups, as well as their awareness of 3D printing technology, willingness to try 3D printed food and meat (steak).

Methodology

Quantitative data were collected through a questionnaire-based consumer survey in three selected European countries, geographically representing Southern (France), Central (the Czech Republic), and Western Europe (Ireland). The questionnaire was originally developed in English and translated into Czech and French. It was pre-tested with a small group of volunteers and based on their recommendation some items were re-formulated and clarified. The online questionnaire was shared via a link to Google Forms (Google, Mountain View, US) through different media, such as Facebook groups focused on people with meat-restricted diets (i.e. Vegetariánství, Zdravý flexitarian), and professional networks focused on food consumption,

to reach potential respondents. Participation was voluntary and self-administered to all participants who answered the questionnaire anonymously. Approximately 10 min were required to complete the questionnaire. The sample of participants included 571 consumers from the three selected European countries, namely from Czechia (205), France (202), and Ireland (164). The data were collected from July to November 2022.

The cross-sectional questionnaire consisted of 11 multiple-choice questions focused on conventional meat consumption habits and attitudes to 3D printed meat. The complex conceptual design of the research is summarized in Figure 1. The questionnaire was divided into four categories that the study aimed to investigate: (i) conventional meat consumption habits, (ii) factors affecting buying behaviour, (iii) knowledge about 3D printed products, and (iv) willingness to try 3D printed food and meat. All participants were asked to evaluate their meat consumption habits according to the following categories: meat eater (eating red meat, fish and chicken), flexitarian (consciously reducing meat intake, but eating meat now and then), pollotarian (eating no red meat, but eating fish, chicken and other poultry), pescatarian (eating no red meat or chicken, but eating fish and shellfish), vegetarian (eating no red meat, chicken, and fish, but eating either eggs and/or dairy products), vegan (eating meatless and no products of animal origin) (De Backer & Hudders, 2015). The questions were focused on reasons influencing meat consumption habits, factors influencing meat purchase decisions and sensory aspects of meat quality evaluation.

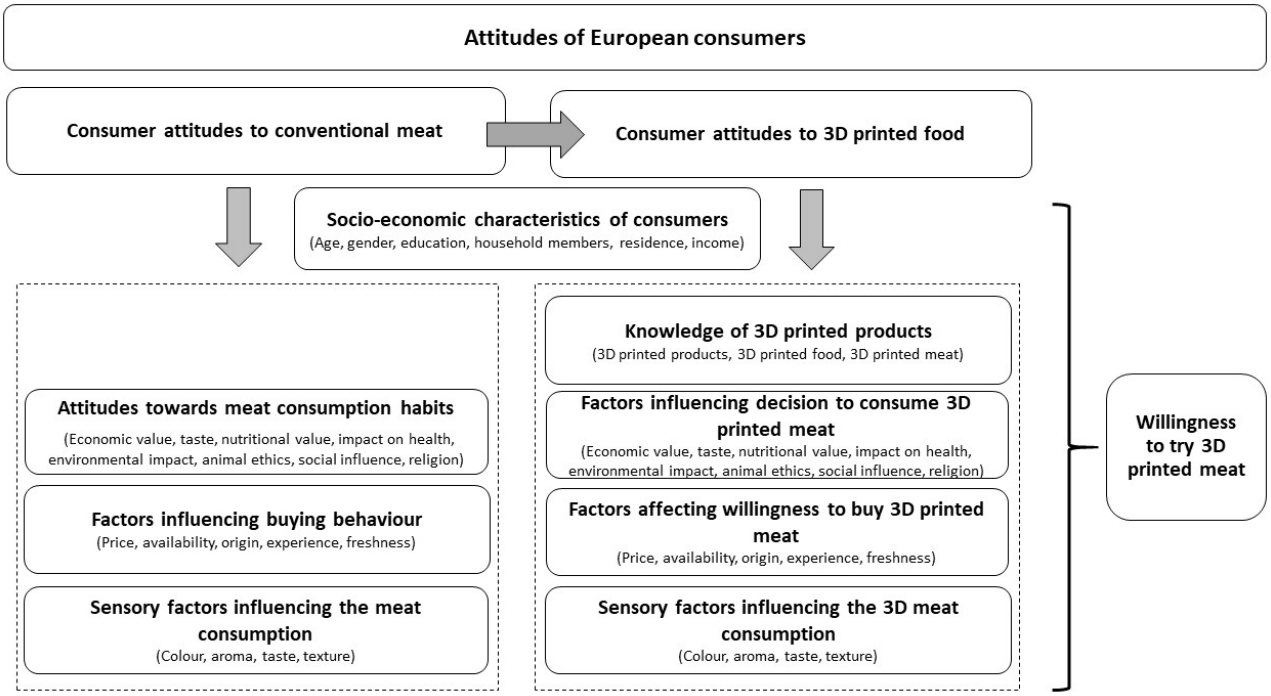


Figure 1: The conceptual design of the research

Afterwards, knowledge about 3D printed products was investigated at three levels: knowledge about 3D printed products, 3D printed foods, and 3D printed meat. The questionnaire then provided a short overview of the main benefits of 3D printed meat as follows: nutritional value (customization of nutritional composition e.g., fat reduction), reduction of health risks (control of diseases transmission from animal production and meat processing), environmental impact (reduction of greenhouse gas emissions, land and water use, food waste), animal ethics (reduced number of slaughtered animals), and product quality (uniformity of size and sensory properties, decreased pre-cooking handling). The procedure for preparing meat from a 3D printer is highlighted in Figure 2, which was provided to the respondents.

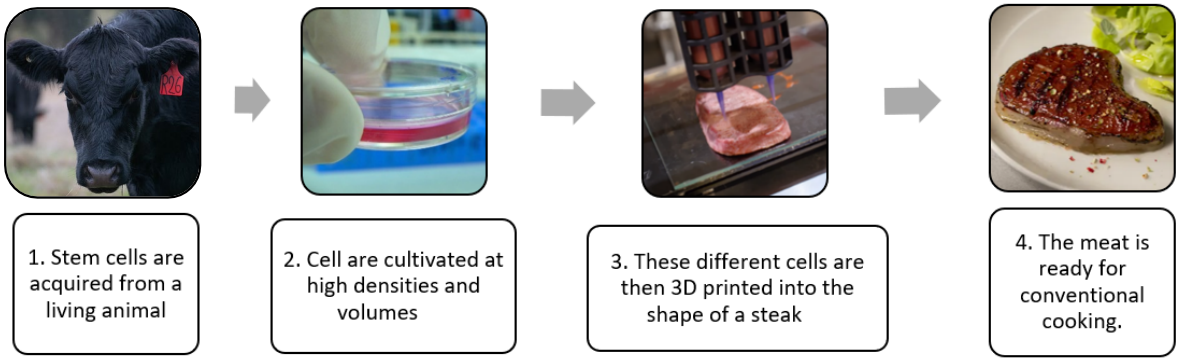


Figure 2: Step-by-step process of 3D printed steak production provided in the survey

This was followed by questions focused on their interest in trying 3D printed products, factors that would influence their decision to consume meat from a 3D printer, willingness to buy 3D printed meat, and which conventional meat quality factors they choose to manipulate using 3D printing. Responses were reported using a 5-points Likert scale, ranging from 1= strongly disagree, through 3 = neither disagree nor agree to 5 = strongly agree. At the end of the questionnaire, the following sociodemographic characteristics of the participants were assessed: nationality, gender, age, education, household size, religion, residency, and income.

Statistical Analyses

According to the meat consumption habits, the participants were grouped into following three consumer groups: meat consumers (representing meat eaters and flexitarians), selective meat consumers (including pollotarians and pescatarians) and meatless consumers (representing vegetarians and vegans). With aim to determine the association between meat consumption attitudes and factors affecting 3D printed meat consumption, data were then analysed using the Kruskal-Wallis and Wilcoxon Matched Pairs tests. Emphasis was placed on a detailed analysis of the behaviour of participants based on their meat consumption habits. Differences between independent variables were considered statistically significant at $p < 0.05$. Statistical analyses were performed using Statistica, version 13.4 (TIBCO Statistica, CA, USA, 2018).

Path analysis was utilized as a confirmatory, multivariate tool. Path analysis provides a set of univariate equations that are solved simultaneously and, therefore, are better suited for studying multiple processes in complicated systems (Shipley, 2002), especially when the studied variables (answers from the questionnaires) are highly correlated (Schumacker & Lomax, 2004). The first diagram was conceptualised to understand the effects of the different questions on four latent variables (attitudes towards meat consumption habits, factors influencing buying behaviour, sensory factors influencing conventional meat consumption, socio-economic factors of the respondents) and the effect of these on the target variable “Meat consumption habits”. The second diagram was conceptualised to understand the effects of the different questions on four dummy variables (knowledge of 3D printed products, factors influencing decision to consume 3D printed meat, factors affecting willingness to try 3D printed meat, and socio-

economic factors of the respondents) and the effect of these and the conventional meat consumption habits on the target variable "Interest in 3D printed meat". Questionnaires with missing values were excluded from the dataset to fit the requirements of the model. Thus, the final datasets were n=547 and n=559, respectively. The list of variables is provided in the Table 1.

Table 1. List of variables, and their codes, used in the Path model

Aspects of consumption	Factors/Statements	Code
Attitudes towards meat consumption habits (Att)	Economic value/benefits	Att1
	Taste	Att2
	Nutritional value	Att3
	Impact on health	Att4
	Environmental impact	Att5
	Animal ethics	Att6
	Social influence	Att7
	Religious reasons	Att8
Factors influencing buying behaviour (BB)	Price	BB1
	Availability	BB2
	Origin	BB3
	Experience	BB4
	Freshness	BB5
Sensory factors influencing the meat consumption (Sens)	Colour	Sens1
	Aroma	Sens2
	Taste	Sens3
	Texture	Sens4
Knowledge of 3D printed products (Know)	I have heard about 3D printed products	Know1
	I know how a 3D printer works	Know2
	I have heard about 3D printed food	Know3
	I know how 3D printed food works	Know4
	I have heard about 3D printed meat	Know5
Factors influencing decision to try 3D printed meat (Dec)	Economic value/benefits	Dec1
	Taste	Dec2
	Nutritional value	Dec3
	Impact on health	Dec4
	Environmental impact	Dec5
	Animal ethics	Dec6
	Social influence	Dec7
	Religious reasons	Dec8
Factors affecting willingness to try 3D printed meat (Will)	Price	Will1
	Availability	Will2
	Origin/Traceability	Will3
	Previous eating experience	Will4
	Freshness	Will5

Socio-economic factors of the respondents (SE)	Gender	SE1
	Age category	SE2
	Highest level of education	SE3
	Number of household members	SE4
	Residential area	SE5
	Net monthly household income (in EUR)	SE6

Since the target variables in the model: Meat consumption habits and Interest in 3D meat, were not normally distributed, Generalised Least Squares was used as the estimation method (Shipley, 2002). Due to the large number of explanatory variables, exceeding the solving capacity, the models were solved in two steps. In the first step, partial models revealed the effects of each group of explanatory factors (further grouped in latent variables) on the target variable (the solved partial models can be found in Supplementary Material 1). These models also included all the covariation possibilities between the explanatory variables and kept all the arrows optional. The models for Attitude and decision-making also accounted for a large, unsolvable number of paths; thus, those paths with a contribution over 0.15 were fixed in the model while the rest remained as optional. In the second step, the full models were built by including the variables selected in the previous step, ordered by their contribution to the model (full designs can be found in Supplementary Material 2). In the final models, only the paths connecting the latent variables and their effects on the target variable were kept as optional.

The statistical significance of the variables included in the solved models was assessed through critical ratios (the ratio mean/SE, which gives a z score allowing assessment of the P value for each variable; Schumacker & Lomax, 2004). Selection of the most plausible models was based on ΔAICc (AICc standardized by setting 0 value to the lowest value achieved). Goodness-of-fit was assessed by two indices: Parsimony-adjusted Comparative Fit Index (PCFI) and Root Mean Square Error of Approximation (RMSEA). PCFI ranges between 0 and 1 and the higher the value, the better, preferably greater than 0.9. In contrast, RMSEA shows a better Goodness-of-fit, preferably lower than 0.05. These indices were selected because they perform well with large sample sizes, although they may be penalised by complex models (Schumacker & Lomax 2004). Thus, Chi-square, the most-used index, was discarded because of the large sample size. Path analyses were performed in Amos 26 for IBM SPSS Statistics.

Results

A total of 571 participants completed the survey, with the majority of respondents being women (62%). A detailed description of the socio-economic characteristics of the participants is given in Table 2. The largest age group was represented by the youngest age category (18-30 years). In terms of education, respondents with a university education dominated (81%). The representation of participants living in the three selected countries is relatively equal, at around 30% from each country. Although, the share of participants from cities (70%) outweighed respondents from rural areas, respondents reported household income in all income categories, with a slight preponderance in the lowest income category (26%; < 1,000 EUR/month). The number of household members varied, with participants from two-member households being most-frequent (25%). From the point of view of religion, atheists represented the majority (60%), while the second most numerous were Christians (34%).

Regarding meat consumption habits, the majority were meat consumers (74%), who eat meat regularly, followed by meatless consumers (17%), who do not eat meat at all. The third group consists of selective meat consumers (9%), who eat only certain types of meat. In all these groups, the majority of participants were university-educated young women, living in cities. The highest number of individuals who abstain from consuming meat resides in the Czech Republic, whereas the lowest number is found in Ireland. The income categories of the participants differ according to their meat consumption habits; meatless consumers belong predominantly (32%) to the category with a household income of 1,000-2,000 EUR/month, whilst the highest proportion of meat consumers and selective meat consumers fell within the up to 1,000 EUR/month income category. Regarding religion, in all three groups more than half are atheists, followed by Christians.

Table 2 Socioeconomic characteristics of the respondents according to their meat consumption habits

Variables	All consumers		Meat consumption habits					
			Meat consumers		Selective meat consumers		Meatless consumers	
	N= 571		N = 424	74.3%	N = 52	9.1%	N = 95	16.6%
Gender								
Female	353	61.8	241	56.8	41	78.8	71	74.7
Male	218	38.2	183	43.2	11	21.2	24	25.3
Age								
18-30	383	67.1	283	66.7	44	84.6	56	58.9
31-40	100	17.5	64	15.1	6	11.5	30	31.6
41-50	57	10.0	51	12.0	0	0.0	6	6.3

51-60	24	4.2	19	4.5	2	3.8	3	3.2
60+	7	1.2	7	1.7	0	0.0	0	0.0
Education								
High School (secondary)	105	18.3	57	13.4	12	23.1	35	36.8
University (tertiary)	466	81.3	365	86.1	40	76.9	60	63.2
Country								
Czechia	205	35.9	117	27.6	23	44.2	65	68.4
France	202	35.4	168	39.6	12	23.1	22	23.2
Ireland	164	28.7	139	32.8	17	32.7	8	8.4
Residential area								
Urban	400	70.1	294	69.3	34	65.4	72	75.8
Rural	171	29.9	130	30.7	18	34.6	23	24.2
Household income (EUR/month)								
≤ 1000	149	26.1	107	25.2	20	38.5	22	23.2
1001 – 2000	130	22.8	92	21.7	8	15.4	30	31.6
2001 – 3000	109	19.1	72	17.0	9	17.3	28	29.5
3001 – 4000	77	13.5	60	14.2	9	17.3	8	8.4
4001+	106	18.6	93	21.9	6	11.5	7	7.4
Household members								
1	119	20.8	84	19.8	13	25.0	22	23.2
2	143	25.0	92	21.7	15	28.8	36	37.9
3	86	15.1	64	15.1	4	7.7	18	18.9
4	118	20.7	96	22.6	10	19.2	12	12.6
5	64	11.2	52	12.3	6	11.5	6	6.3
6+	41	7.2	36	8.5	4	7.7	1	1.1
Religion								
None	346	60.6	234	55.2	30	57.7	82	86.3
Christian	191	33.5	167	39.4	16	30.8	0	0.0
Islam	14	2.5	11	2.6	3	5.8	8	8.4
Jewish	5	0.9	4	0.9	0	0.0	1	1.1
Hindu	5	0.9	5	1.2	0	0.0	0	0.0
Buddhist	5	0.9	2	0.5	1	1.9	2	2.1
Other	5	0.9	1	0.2	2	3.8	2	2.1

Overall, 72% of participants reported familiarity with 3D printing products. However, only half of the respondents were aware of 3D printed food, and 42% confirmed knowledge of 3D printed meat. Despite this, 67% of participants expressed interest in 3D printed foods such as sweets or pasta, whereas interest in 3D printed meat was lower (51%). Significant differences in awareness of 3D printing products were observed among different groups based on their meat consumption habits (Table 3). The group of selective meat consumers exhibited the highest overall awareness of 3D printed products, followed by the meatless consumers group. Interestingly, the meatless consumers group demonstrated a higher awareness of 3D printed

meat. All three consumer groups expressed equal interest in trying 3D printed food. However, a significant difference was observed in the willingness to try 3D printed meat ($p < 0.001$). The group of meat consumers indicated a willingness to try 3D printed meat, whereas the meatless consumer group was the least interested in trying it.

Table 3 Comparison of the consumer awareness of 3D products and willingness to try 3D printed food and meat products, according to their meat consumption habits

	All consumers	**Meat consumers**	**Selective meat consumers**	**Meatless consumers**	
	N = 571	**N =424**	**N = 52**	**N = 95**	
Statements		**Mean ± S.E.**			**p-value**
I have heard about 3D printing products	3.7 ± 0.06	3.5 ± 0.07	4.2 ± 0.14	4.0 ± 0.13	**<0.001**
I know how a 3D printer works	3.2 ± 0.05	3.2 ± 0.06	3.1 ± 0.18	3.4 ± 0.13	0.149
I have heard about 3D printed food	3.0 ± 0.06	2.8 ± 0.07	3.6 ± 0.21	3.6 ± 0.14	**<0.001**
I know how 3D printed food works	2.0 ± 0.05	2.0 ± 0.06	2.1 ± 0.17	2.7 ± 0.12	**0.046**
I have heard about 3D printed meat	2.7 ± 0.07	2.6 ± 0.08	3.0 ± 0.22	3.1 ± 0.16	**0.014**
I know how 3D printed meat works	1.8 ± 0.05	1.8 ± 0.05	1.7 ± 0.13	2.0 ± 0.12	0.362
I would try 3D printed meat	3.2 ± 0.06	3.4 ± 0.07	3.0 ± 0.21	2.2 ± 0.15	**<0.001**
I would try other 3D printed food (e.g., confections, pasta)	3.6 ± 0.06	3.6 ± 0.07	3.7 ± 0.16	3.6 ± 0.15	0.997
Willingness to try 3D printed meat vs. food (p-value)	**<0.001**	**<0.001**	**0.001**	**<0.001**	

Note: Numbers in bold are significant at $p < 0.05$; Ranking scale: 1= Strongly disagree, to 5 = Strongly agree.

Furthermore, the effect of attitudes towards conventional meat consumption habits, factors influencing buying behaviour, sensory quality factors, and socio-economic factors were analysed for conventional meat consumption habits. Figure 2 shows the most parsimonious model explaining meat consumption habits among selected European consumers. Up to 10 models had $\Delta AICc=0$; however, the selected model had the best Goodness-of-fit indices: lowest RMSEA value (0.075) and the highest PCFI (0.552). This model shows that sensory factors (standardized regression weight = -0.57; hereafter SRW) and socio-economic factors (SRW = -0.35) are the key aspects explaining conventional meat consumption habits. These latent variables are mainly explained by the factors taste (Sens3; SWR = 0.89), aroma (Sens2; SWR = 0.86) and colour (Sens1; SWR = 0.82), and number of household members (SE4; SWR = 0.32), gender (SE1; SWR = 0.23) and level of education (SE3; SWR = 0.22), respectively. The model also highlights strong covariation among the latent variables: sensory and buying behaviour (SWR = 0.76), socio-economic and attitude (SWR = -0.69), sensory and socio-

economic (SWR = 0.53), socio-economic and buying behaviour (SWR = 0.051), sensory and attitude (SWR = -0.47), and attitude and buying behaviour (SWR = -0.39).

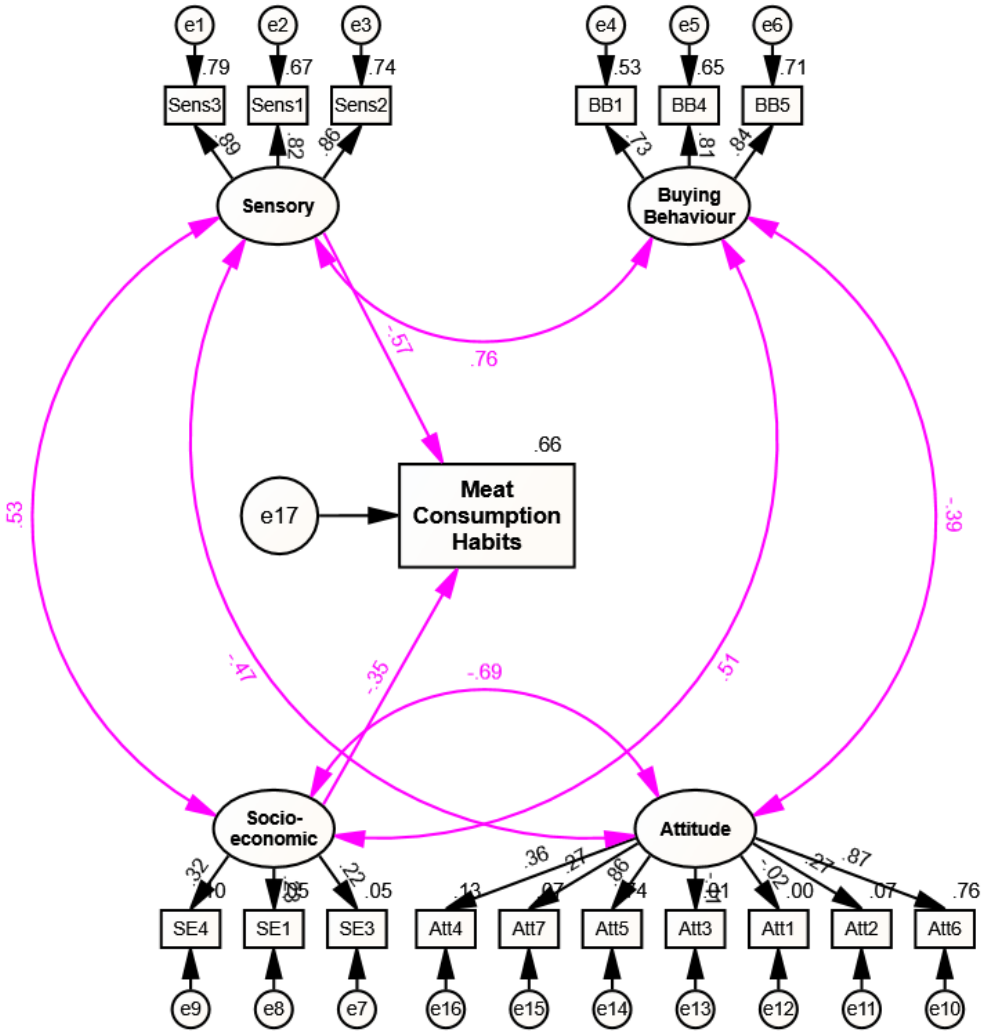


Figure 2: Factors influencing conventional meat consumption habits among European consumers

Note: Att1= Economic value/benefits, Att2= Taste, Att3= Nutritional value, Att4= Impact on health, Att5= Environmental impact, Att6= Animal ethics, Att7= Social influence, BB1= Price, BB4= Experience, BB5= Freshness, Sens1= Colour, Sens2= Aroma, Sens3= Taste, SE1= Gender, SE3= Highest level of education, SE4= Number of household members

Subsequently, the factors influencing willingness to try 3D printed meat, taking in account conventional meat consumption habits of the consumers, were analysed. Figure 3 showed the most parsimonious model explaining the interest in 3D printed meat among

European consumers. Up to 11 models had ΔAICc=0; however, the selected model had the best goodness-of-fit indices: lowest RMSEA value (0.053) and the highest PCFI (0.738). This model showed that decision-making factors (SWR = 0.70) and conventional meat consumption habits (SWR = -0.23) were the key aspects explaining the interest in 3D printed meat among European consumers. Decision-making was itself explained by taste (Dec2; SWR = 0.85), economic value (Dec1; SWR = 0.83), environmental impact (Dec5; SWR = 0.72) and religious reasons (Dec8; SWR = 0.60). Covariation among the latent variables was also studied. The model highlighted important covariations as those between decision-making and willingness (SWR = 0.85), decision-making and socio-economic (SWR = -0.52), socio-economic and willingness (SWR = 0.40), knowledge and decision-making (SWR = 0.27), and willingness and knowledge (SWR = -0.23).

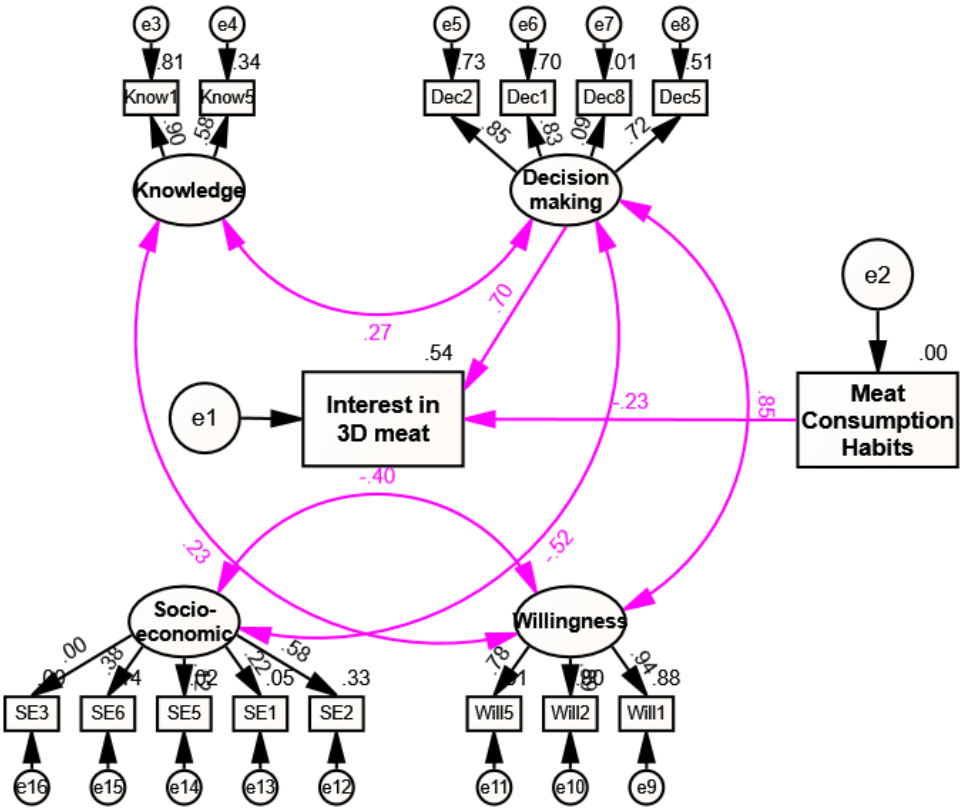


Figure 3: Factors influencing willingness to try 3D printed meat among European consumers

Note: Know1= I have heard about 3D printed products, Know5= I have heard about 3D printed meat, Dec1= Economic value/benefits, Dec2= Taste, Dec5= Environmental impact, Dec8= Religious reasons, Will1= Price, Will2= Availability, Will5= Freshness, SE1= Gender, SE2=Age, SE3= Highest level of education, SE5= Residential area, SE6= Net monthly household income

Finally, we compared three groups of consumers based on their conventional meat consumption habits and their attitudes influencing the willingness to consume conventional meat versus 3D printed meat (Table 4). Within the meat consumer group, significant differences were observed in preferences for conventional meat versus 3D printed meat concerning taste, environmental impacts, and animal ethics. For the group of selective meat consumers, a significant difference was noted only in the economic value/benefits factor ($p < 0.05$). Conversely, for the group of meat-free consumers, factors such as economic and nutritional value, environmental impact, and animal ethics significantly differed between conventional, and 3D printed meat ($p < 0.05$).

From the perspective of factors influencing consumer purchasing behaviour, freshness, previous eating experience, and price were predominant considerations for conventional meat. In contrast, price, origin/traceability, and freshness were key factors when considering the willingness to consume 3D printed meat. Significant differences in factors influencing meat purchases were also observed among three consumer groups. For the meat consumer group, differences were mainly in terms of price, previous eating experience, and freshness. Among meatless consumers, statistically significant differences ($p < 0.001$) were observed for all factors, including price, availability, origin, previous eating experience, and freshness.

Sensory parameters determining consumption also differed significantly between conventional and 3D printed meat. In the meat consumer and meatless consumer groups, all sensory factors showed significant differences ($p < 0.001$). However, in the group of selective meat consumers, differences between factors for conventional meat and 3D printed meat were not significant and evaluated individual parameters similarly for both methods of meat production.

Table 4 Factors influencing willingness to consume and purchase conventional versus 3D printed meat

	All consumers			Meat consumers			Selective meat consumers			Meatless consumers		
	Conventional meat	3D printed meat		Conventional meat	3D printed meat		Conventional meat	3D printed meat		Conventional meat	3D printed meat	
	Mean ± S.E		p-value	Mean ± S.E		p-value	Mean ± S.E		p-value	Mean ± S.E		p-value
Factors influencing willingness to consume												
Economic value/benefits	3.3 ± 0.05	3.3 ± 0.06	0.439	3.5 ± 0.06	3.4 ± 0.06	0.152	2.9 ± 0.17	3.4 ± 0.17	**0.006**	2.5 ± 0.15	2.9 ± 0.15	**0.011**
Taste	3.9 ± 0.05	3.6 ± 0.06	**< 0.001**	4.1 ± 0.05	3.6 ± 0.07	< 0.001	3.8 ± 0.18	3.8 ± 0.17	0.985	2.8 ± 0.17	3.2 ± 0.15	0.066
Nutritional value	3.4 ± 0.05	3.4 ± 0.06	0.455	3.5 ± 0.06	3.4 ± 0.06	0.077	3.3 ± 0.19	3.7 ± 0.18	0.061	2.6 ± 0.14	3.3 ± 0.15	**0.001**
Impact on health	3.6 ± 0.05	3.6 ± 0.06	0.862	3.6 ± 0.05	3.6 ± 0.06	0.922	3.8 ± 0.17	3.8 ± 0.17	0.647	3.6 ± 0.14	3.4 ± 0.15	0.460
Environmental impact	3.7 ± 0.05	3.8 ± 0.05	**0.002**	3.4 ± 0.06	3.7 ± 0.06	**< 0.001**	4.1 ± 0.14	4.3 ± 0.16	0.170	4.5 ± 0.10	3.9 ± 0.15	**0.002**
Animal ethics	3.5 ± 0.05	2.8 ± 0.06	0.213	3.3 ± 0.06	3.4 ± 0.07	**0.005**	3.9 ± 0.15	4.1 ± 0.17	0.313	4.5 ± 0.11	3.9 ± 0.15	**0.003**
Social influence	2.7 ± 0.05	3.6 ± 0.06	0.318	2.7 ± 0.06	2.8 ± 0.06	0.632	2.7 ± 0.17	3.0 ± 0.18	0.086	2.5 ± 0.15	2.6 ± 0.15	0.737
Religious reasons	1.5 ± 0.04	1.6 ± 0.04	**0.050**	1.5 ± 0.04	1.6 ± 0.05	**0.039**	1.7 ± 0.16	1.8 ± 0.19	0.388	1.4 ± 0.10	1.4 ± 0.08	0.931
Factors determining buying behaviour												
Price	3.3 ± 0.07	3.6 ± 0.06	**0.005**	3.8 ± 0.06	3.7 ± 0.06	**0.021**	3.5 ± 0.24	4.1 ± 0.17	0.086	1.0 ± 0.17	3.1 ± 0.16	**< 0.001**
Availability	3.0 ± 0.07	3.4 ± 0.06	**< 0.001**	3.4 ± 0.07	3.5 ± 0.06	0.904	3.4 ± 0.22	3.8 ± 0.17	0.158	1.0 ± 0.16	3.0 ± 0.15	**< 0.001**
Origin/traceability	3.2 ± 0.08	3.5 ± 0.06	**0.022**	3.6 ± 0.07	3.5 ± 0.07	0.062	3.5 ± 0.23	3.7 ± 0.18	0.919	1.2 ± 0.20	2.9 ± 0.15	**< 0.001**
Previous eating experience	3.4 ± 0.08	3.4 ± 0.06	0.478	4.0 ± 0.07	3.5 ± 0.06	**< 0.001**	3.7 ± 0.20	3.7 ± 0.17	0.987	1.0 ± 0.17	3.3 ± 0.16	**< 0.001**
Freshness	3.6 ± 0.08	3.5 ± 0.06	**0.050**	4.2 ± 0.07	3.6 ± 0.06	**< 0.001**	4.0 ± 0.24	3.9 ± 0.17	0.499	1.1 ± 0.18	2.9 ± 0.15	**< 0.001**
Quality parameters determining consumption												
Colour	3.2 ± 0.07	2.9 ± 0.05	**0.001**	3.8 ± 0.06	3.0 ± 0.05	**< 0.001**	2.9 ± 0.27	3.1 ± 0.18	0.480	0.7 ± 0.14	2.8 ± 0.12	**< 0.001**
Aroma	3.3 ± 0.07	3.2 ± 0.05	0.267	3.9 ± 0.06	3.2 ± 0.06	**< 0.001**	2.9 ± 0.25	3.3 ± 0.17	0.209	0.7 ± 0.14	3.0 ± 0.13	**< 0.001**
Taste	3.8 ± 0.07	3.3 ± 0.05	**< 0.001**	4.5 ± 0.05	3.3 ± 0.06	**< 0.001**	3.8 ± 0.23	3.4 ± 0.18	0.057	0.7 ± 0.14	3.1 ± 0.13	**< 0.001**
Texture	3.5 ± 0.07	3.2 ± 0.05	**0.001**	4.1 ± 0.05	3.3 ± 0.06	**< 0.001**	3.5 ± 0.23	3.4 ± 0.17	0.476	0.7 ± 0.14	3.0 ± 0.12	**< 0.001**

Note: Numbers in bold are significant at $p < 0.05$; Ranking scale 1=Strongly disagree, to 5 = Strongly agree.

Discussion

In general, meat consumption habits differ among consumers worldwide and these habits are affected or constrained by various factors such as socio-economic, cultural attitudes (e.g., religion aspects) or ethical concerns, including animal rights, environmental protection, and health. In this study, the predominant groups of respondents were mainly women, university graduates and between 18 to 30 years old. Similar to previous studies, these groups are mostly interested in topics focused on new technologies, concerns related to the environment, animal welfare, sustainable consumption, or healthy nutrition (Bryant, 2019; Michel, Hartmann, & Siegrist, 2021a). For example, women show more positive attitudes toward a meatless diet and total meat intake in comparison with men due to a greater health consciousness (Fagerli & Wandel, 1999; Michel et al., 2021a). Moreover, women are also usually the family member purchasing food for the household, and thus have an impact on the household consumption habits to some extent.

Overall, the findings showed that the taste of meat, impact on health, and nutritional value were the most important factors influencing conventional meat consumption. Conclusions from previous studies indicated that consumers underestimate the impact of meat consumption and production on environment and their willingness to change their meat-eating habits is low (Hartmann & Siegrist, 2017). The importance of the impact of a healthy diet against malnutrition and against non-communicable diseases (i.e. diabetes, heart disease, stroke and cancer) is actively emphasized by the WHO, which, among other things, recommends eat low-fat dairy foods and lean meats or trim visible fat from meat (WHO healthy diet, 2024). The findings also showed that environmental impact and animal ethics play a key role in the decision-making of meatless consumers. Although, several consumer studies predicted an increase in eating habits such as flexitarianism or vegetarianism, and at the same time meat eaters consider a vegetarian and vegan diet ethical, good for the environment, and healthy, they nevertheless consider it difficult, unpleasant and expensive (Bryant, 2019; Michel, 2021).

The respondents of this survey showed a high knowledge of 3D printed products, probably supported by a wide range of products currently used in all fields, from engineering to the production of medical devices, and their popularity has been growing in recent years even

in household use. An example of a very good promotion of 3D printers is the Czech company Prusa Research, which was founded as a single-man start-up in 2012 and is well-known worldwide thanks to its open-source approach (Prusa, 2024). On the other hand, awareness about 3D printed food and meat among the respondents was lower. This is in line with previous studies in Switzerland and Australia (Brunner, 2018; Lupton, 2018). These results are not surprising, as 3D printed food is not yet commonly available nowadays. However, the awareness among the population is gradually expanding among different target groups. For instance, the world's first restaurant serving 3D printed food opened in London in 2016 (Lee et al., 2021). Additionally, tutorials for high school students that show specific products from 3D printers including sweets are now being conducted in Czech TV programmes (ČT., 2023). Interestingly, meatless consumers reported significantly higher knowledge about 3D printed food, including 3D printed meat. This can be explained by the fact that these consumers usually actively search for different types of meat alternatives. Therefore, this group could play a key role in spreading awareness of 3D food products. When we looked at the willingness to try 3D printed food, the results showed that consumers are interested in trying these products, particularly sweets or pasta. Conversely, the willingness to try 3D printed meat was significantly lower in comparison to other food products. Similarly to previous study, although consumers rated 3D printed chicken as healthy and natural, their willingness to try these products was low (Lupton, 2018). From the point of view of consumers, the disgust and safety of the production were among the reasons for reluctance to try 3D printed meat (Manstan, 2020).

The results of our study also showed significant differences between individual groups of respondents according to conventional meat consumption habits. While the group of meat consumers reported willingness to try 3D printed meat, the meatless consumers were significantly less interested in trying it. The key role in spreading awareness will therefore be played by a well-designed communication strategy that emphasizes the positive effects and at the same time the opportunity to try 3D printed meat. Consumers in the category of innovators and early adopters, who can expand their knowledge and possibly their first experiences, will therefore play an important role in passing on information about 3D printed food. This is also supported by previous findings that people tend to adopt the eating behaviour of their peers (Higgs, 2016, Michel, 2021). Raising awareness among potential consumers could be done via tasting and food demonstrations. For example, a wide spectrum of recipes and tastings is offered by the Austrian company Revo Foods, which focuses on the production of 100% plant-based

seafood that has great nutritional value, but at the same time helps reduce overfishing and relieve pressure on the marine ecosystem (Revo Foods, 2023). Active promotion is also on the part of the Israeli company Aleph Farms, which as the world's first company presented a 3D printed beef steak (Aleph Farms, 2024).

The respondents stated that freshness of meat, followed by previous eating experience and price were among the factors influencing their buying behaviour of conventional meat. The study by Bryant (2019) reported that while meat consumers agree with the ethical and environmental arguments in favour of vegetarianism/veganism, they do not adhere to these diets for practical reasons related to taste, cost, and convenience. According to OECD report (2024), meat consumption is related to living standards, diet, and price, and thus meat demand is associated with higher incomes. Our results also showed that the sensory parameters of meat such as taste, aroma and colour are the key aspects explaining meat consumption habits, which aligns with previous research with American consumers, that showed they also considered taste and overall meat quality as key attributes (Tonsor & Lusk, 2022). Previous findings also stated that meat alternatives should be similar to meat in terms of taste, texture and ease of preparation, and that it is preferable to focus on replicating processed meat products offered at competitive prices rather than trying to imitate cuts of meat such as steak (Michel, Hartmann, & Siegrist, 2021b).

Our findings indicated that price, origin/traceability, and freshness were also crucial factors influencing the willingness to try 3D printed meat. Generally, product price is a significant aspect impacting consumers' purchasing intentions. As the production of 3D printed meat is currently in the developmental phase, the market price will depend on the final production costs and competitive dynamics, as well as expenses related to raising awareness among potential customers. A previous study also showed that the most important aspect for potential consumers of 3D printed food is natural content, followed by the possibility of creativity (Lee et al., 2021). From the point of view of potential consumers of 3D printed meat, sensory parameters such as taste, texture and aroma were reported as key aspects related to willingness to try 3D printed meat. This is a huge advantage of 3D food printing technology used for all types of food in digital gastronomy, which makes it possible to adapt the shape, colour, taste or nutrition of food according to customer preferences and thus create tailor-made food (Lipson & Kurman, 2013). In order to overcome food neophobia and build trust in the use of 3D printed food technology, it is therefore necessary to spread awareness through well-designed communication about the potential benefits of printing, which include, for example,

the reduction of food waste, environmental sustainability, especially through the more efficient and effective use of food ingredients in terms of storage, transport, preparation and reuse of discarded food (Lupton and Turner, 2016a, Lupton and Turner, 2018). However, especially for 3D printed meat, which is perceived more cautiously by customers, it will also be important to emphasize the taste of the meat produced in this way, including the positive effects on health and the environment.

The study has several potential limitations. One of them is the relatively low number of respondents. As part of data collection, it was evident that this topic was sensitive and potential respondents refused to participate in the research after reading the name and purpose of the survey. This often happened in the online environment as well, that some Facebook groups focused on healthy nutrition, for example, refused to expand this questionnaire. There was also a low willingness to cooperate on the research among the restaurant operators contacted. The results of this study were also influenced by the current situation, that the respondents mostly do not have personal experience with trying 3D printed food and therefore only express their attitudes from the point of view of potential customers. Early 2024, Israeli food technology startup Aleph Farms confirmed it received regulatory approval to sell steak grown from cow cells (Aleph Farms, 2024). However, the product is currently not available on the market and therefore customers cannot rate it based on their experience. As a recommendation for further research, it would be ideal for participants to directly experience samples of 3D printed meat and be able to rate the sensory qualities. This could provide further insights for the product development. Finally, a relatively high proportion of vegetarians was included in our research on purpose in order to analyse the differences between individual groups and to find out whether 3D printed meat would be an alternative for the target group of meatless consumers. According to national statistics, the representation of vegetarians in EU countries is on average around 5% (OECD, 2024). Our sample included 17% meatless consumers, with the largest number of meatless consumers from the Czech Republic (32%), followed by France (11%) and Ireland (5%).

Conclusions

This study analysed consumer attitudes of European consumers towards the consumption of 3D printed products, particularly focusing on 3D printed meat, which uses cultured cells to produce meat products. Majority of the respondents reported a high familiarity with 3D printing products, but less than half of them knew 3D printing meat. The willingness to try 3D printed

meat among potential customers was significantly lower than for other types of 3D printed food. Although meatless consumers reported a higher awareness of 3D printed meat, they were not interested in trying the product. On the contrary, consumers who consume conventional meat showed the highest interest in trying 3D meat. Factors such as taste, economic value, environmental impact have been shown to be key in the decision making of potential customers. To address food neophobia and build trust in 3D printed food technology, a well-designed communication strategy that emphasizes its positive effects on the environment will play a key role in the promotion of 3D printed meat and raising awareness among consumers. At the same time, from the point of view of producers, it will be crucial to focus on the resulting taste of 3D printed meat, while the final price of the meat will also be an important aspect. Further studies should focus on the sensory evaluation of 3D printed meat samples so that it is possible to verify the attitudes of potential customers based on their own experience.

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