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Understanding Italian Consumers' Intentions Toward Sustainable 3D-Printed Savory Snacks: An Extended Theory of Planned Behavior Approach

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Abstract

To address climate change, reducing food loss along the production and supply chain is a global priority. Addressing this challenge requires a shift in agrifood systems toward greater sustainability, in which new technologies and novel foods appear as promising strategies. Among emerging novel foods, 3D-printed foods are an interesting new food technology for food loss reduction, resource optimization, and by-product valorization. However, to reach market success, it needs consumer acceptance, a topic far unexplored, particularly in the Italian context. To fill the literature gap, this article investigates Italian consumers' intention toward 3D-printed savory snacks using an extended Theory of Planned Behavior, based upon the relevant literature. Survey data were collected, and partial least squares structural equation modeling was performed to test research hypotheses. Results show that *attitude* and *subjective norms* are the strongest predictors of purchase *intention*. In addition, *perceived usefulness* is shown to be a powerful construct, positively impacting *attitude* and *subjective norms*, while *self-identity as a green consumer* reinforces perceptions of the benefits of 3D-printed foods. *Sensory appeal* impacts consumer *attitude*. These insights have practical policy and micro-level applications, suggesting tailored strategies, educational campaigns, and supportive policies and marketing campaigns for fostering acceptance of 3D printing in the agrifood sector.

Keywords: 3D food printing; food processing innovation; sustainable food production; future food technology; savory snacks; partial least squares structural equation model (PLS-SEM)

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1. Introduction

Global food systems are increasingly challenged by environmental degradation, and growing pressure on natural resources [1,2]. Within this context, the agrifood sector plays a crucial role, as it is responsible for a significant share of global greenhouse gas emissions and food losses throughout the entire production cycle [3]. Indeed, while most food waste occurs at the consumption stage, a substantial proportion of losses and waste arises upstream along the food supply chain. Globally, about 13 percent of all food produced is lost between the post-harvest and retail stages [4]. Similarly, within the European Union (EU), nearly half of total food losses and waste occur upstream, with a significant contribution from food manufacturing [5]. Beyond its economic and ethical implications, food loss exacerbates pressure on already scarce natural resources, making its reduction a global priority for achieving sustainable food systems and meeting Sustainable Development Goal 12, particularly target 12.3 [6].

Within this context, novel foods and new food technologies represent promising solutions to improve sustainability in the agrifood sector [7–9]. Among them, 3D food printing stands out for its potential to address multiple environmental and economic challenges simultaneously. 3D printing is an emerging technology that has been applied to several sectors (e.g., medicine, construction, education [10]), including the food industry. By enabling the precise deposition of ingredients layer by layer, 3D food printing allows the optimization of raw material use, the valorization of food by-products, and the reduction in food losses by allowing the printing of the desired amount of food [11]. Furthermore, this technology enables a high degree of product customization in terms of shape, texture, and nutritional composition, opening new opportunities for functional, personalized, and sustainable foods [12–14].

Nevertheless, several economic constraints continue to limit the large-scale adoption of 3D food printing. The technology is still at an early stage of development, and challenges related to scalability and process maturity result in higher production costs compared to conventional manufacturing systems [15]. Consequently, its economic value is not primarily derived from cost reduction, but rather from its capacity to enable high levels of product customization and innovation [12,14,16].

Personalized food products are inherently associated with higher costs, particularly when produced through traditional artisanal methods. In this context, 3D food printing can improve the efficiency and accessibility of mass customization, reducing costs relative to conventional artisanal approaches, while remaining less competitive than mass production in terms of unit costs [17]. From a demand perspective, empirical evidence indicates that consumers are generally willing to pay a premium for 3D-printed foods, particularly when the benefits of personalization, functionality, and innovation are clearly perceived [18].

Building on these economic and technological considerations, the successful market introduction of 3D-printed foods largely depends on consumer acceptance, which remains a critical barrier for many novel foods and food technologies. Previous research consistently shows that consumers often exhibit skepticism and resistance toward unfamiliar food technologies, especially in countries characterized by strong culinary traditions and deep-rooted food cultures [7,19].

This issue is particularly relevant in Mediterranean countries, such as Italy, where food is closely linked to cultural identity and tradition. Some applications of 3D food printing have already been introduced in real markets, such as 3D-printed pasta, which is even considered a delicacy in niche markets [20], and 3D-printed plant-based meat [21]. Despite this, empirical evidence on consumer acceptance remains scarce. Existing studies have demonstrated the technical feasibility of producing 3D-printed savory snacks using typical Italian ingredients, such as cereals and fruits, suggesting that these products could serve as

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an accessible entry point for consumers to approach this technology [22,23]. However, little is known about how Italian consumers perceive these products and which factors drive or hinder their acceptance.

So far international literature on 3D food printing has focused on several main areas. These include technical aspects of 3D food printing, for example, the challenge of developing products that maintain sensory qualities [24], investigating gels and products that can be used for 3D printing and are safe also for consumers with swallowing problems [25,26], and examining the incorporation of antioxidants into 3D printed dough to obtain functional foods [27]. Other studies have discussed how 3D food printers can process byproducts, offering benefits for environmental sustainability [28,29], as well as the improvement of the management of food losses and waste [30–32]. In addition to the environmental sustainability advantages mentioned above, Ben-Ner and Siemsen [33] pointed out that the adoption of 3D food printing by localized food enterprises can enhance economic and social sustainability. To the authors' knowledge, empirical evidence on consumer acceptance of specific and innovative product categories, such as 3D-printed savory snacks, remains scarce, and no studies have yet examined Italian consumers' perceptions and acceptance of these products.

Understanding the drivers of consumer acceptance is therefore essential not only for supporting the diffusion of 3D-printed foods but also for designing effective strategies to orient consumers toward more sustainable dietary choices. Insights into consumers' attitudes, perceptions, and behavioral intentions can help policymakers and firms develop targeted communication strategies, product positioning, and potential nudging interventions aimed at reducing resistance to novel foods and facilitating their integration into everyday diets (e.g., [34]).

In this framework, the present study aims to investigate the drivers of Italian consumers' acceptance of 3D-printed savory snacks. Considering (i) the institutional push towards innovation and digitization, which drives the agrifood sector to remain competitive, (ii) the consumer demand for new sustainable and healthy products, and (iii) the potential role of novel foods and new food technologies, the objective of this study is to investigate the potential driver of acceptance of 3D-printed savory snacks in Italy.

To address this objective, this study proposes an extended model of the Theory of Planned Behavior (TPB [35]) to understand the drivers of Italian consumers' willingness to buy 3D-printed savory snacks. Previous literature highlighted the relevance of the TPB model as a reference framework in the analysis of food-related behaviors oriented toward sustainability [36,37]. However, several authors have pointed out the need to consider additional variables to strengthen the explanatory power of this theory [38–42], particularly when considering pro-environmental behaviors [43–45].

The study is structured as follows: Section 2 presents the theoretical background and hypotheses; Section 3 describes the methodology and Section 4 reports the results. Finally, Sections 5 and 6 discuss conclusions and implications.

2. Theoretical Background

An important part of the literature field has investigated psychological factors that could influence consumer acceptance and practical intention related to 3D-printed food [46]. In particular, several papers have used the TPB [47] to investigate consumer behavior toward 3D-printed food. TPB, developed by Ajazen, assumes that behavioral intention, defined as the propensity to adopt a specific behavior, is influenced by attitude (i.e., the degree to which a person evaluates the behavior positively or negatively), subjective norms (i.e., perceived social pressures from relevant others to perform or not perform a behavior), and perceived behavioral control (i.e., the perceived ease or difficulty of performing a behavior, incorporating both self-efficacy and controllability) [47]. Although there are several other available models, the TPB is one of the most common and frequently used theories in the food field [48], particularly when considering sustainability aspects [37,49].

Specifically focusing on 3D food printing, Yang et al. [50] examined factors affecting consumers' intention and willingness to pay a premium price for 3D-printed food by integrating the TPB model with additional constructs, i.e., Personal Innovativeness, Perceived Compatibility, Perceived Product Value and the Mediating Effect of Intention To Consume 3D-Printed Food. Similarly, Chang [8] investigation used an extension of the TPB with constructs such as sensory appeal, food neophobia, perceived health risk, and environmental friendliness. Moreover, the study of Kamrath et al. [51], combining the TPB with a food technology acceptance model (FTAM), demonstrated the importance of confidence in predicting the intention of the consumer.

The key constructs of the Theory of Planned Behavior (TPB) and the related research hypotheses are discussed in this section. Prior research on innovative food technologies has shown that a favorable attitude strongly predicts the intention to adopt novel foods [8,50]. Accordingly, the first hypothesis of this study is:

H1. *Attitude positively influences the behavioral intention to buy 3D-printed food.*

Subjective norms are also important predictors of behavioral intention in the context of new food technologies [51]. Indeed, if consumers perceive that family, friends, or peers view 3D-printed food positively, their own intention to purchase it will increase. Thus, the second hypothesis of this study is:

H2. *Subjective norms positively influence the behavioral intention to buy 3D-printed food.*

The third element of TPB is perceived behavioral control: consumers who feel confident in understanding and accessing 3D-printed food are more likely to buy it [50]. Therefore:

H3. *Perceived behavioral control positively influences the behavioral intention to buy 3D-printed food.*

Building on the Theory of Planned Behavior (TPB) [47], this study assumes that intention to purchase 3D-printed foods is shaped by attitude, subjective norms, and perceived behavioral control. However, when studying innovative food technologies, the traditional TPB framework may be insufficient to fully explain behavioral intention, as consumers often rely on additional cognitive and affective factors to evaluate technological novelties.

Starting from the study of Hellali and Korai [52], perceived usefulness is expected to influence consumers' attitude and therefore it should also influence subjective norms and perceived behavioral control. Perceived usefulness has been particularly discussed in the Technology Acceptance Model (TAM) [53] and largely introduced in innovation and technology adoption theories. It refers to the degree to which individuals believe that using a technology enhances outcomes or provides valuable benefits. When consumers perceive a food innovation as useful—for instance, more sustainable, efficient, or customizable—they tend to show a better opinion toward it and a stronger willingness to accept it [54]. In the context of novel foods, perceived usefulness can enhance attitude by reinforcing positive beliefs about the innovation's benefits [50,55], and may strengthen subjective norms, as individuals who view the technology as beneficial are more likely to perceive social approval and discuss it favorably within their social groups [19,51]. Lastly, perceived usefulness can also improve perceived behavioral control, as consumers who understand

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and appreciate the advantages of the technology may feel more capable and confident in trying it. Consequently:

H4. *Perceived usefulness positively influences attitude towards purchasing 3D-printed food.*

H5. *Perceived usefulness positively influences subjective norms towards purchasing 3D-printed food.*

H6. *Perceived usefulness positively influences perceived behavioral control towards purchasing 3D-printed food.*

Moreover, according to Hellali et al. [52,55], consumers often show mixed reactions towards innovative food technologies, mainly due to concerns about naturalness, freshness, or safety. Building on this evidence, this study introduced different constructs, as recommended by previous literature [38–42].

Specifically, self-identity as a green consumer is introduced as a predictor of perceived usefulness: Individuals with higher ecological awareness are expected to recognize the benefits of 3D-printed foods for the environment [56]. More specifically, individuals who consider themselves environmentally responsible evaluate sustainable innovations more favorably, recognizing their ecological and social benefits. This self-concept reinforces internal norms and increases the perceived usefulness of green technologies, as consumers align their behavior with their environmental values. In the context of 3D-printed foods, people who identify as "green consumers" are more likely to acknowledge the technology's contribution to sustainability through waste reduction, resource efficiency, and by-product valorization, thus perceiving it as more useful and beneficial. Conversely, risk-aversion related to food technologies such as concerns about safety, ingredient modifications, or reduced freshness may reduce perceived usefulness and lower the intention to purchase [57]. Individuals who are more risk-averse tend to perceive new products as riskier in terms of safety and naturalness, which diminishes their assessment of the technology's utility and benefits. In the case of 3D-printed foods, concerns related to artificiality or the lack of sensory familiarity may lower perceived usefulness and, consequently, willingness to adopt.

H7. *Self-identity as a green consumer positively influences the perceived usefulness of 3D-printed food.*

H8. *Risk aversion negatively influences the perceived usefulness of 3D-printed food.*

Finally, considering the main characteristic of 3D-printed foods, such as the possibility of creating personalized products based on consumers' needs and preferences, this study also introduces the construct of sensory appeal. Accordingly, this paper assesses the following hypotheses:

H9. *Sensory appeal positively influences the perceived usefulness of 3D-printed food.*

To increase the readability of this study, Figure 1 presents the model with the hypotheses.

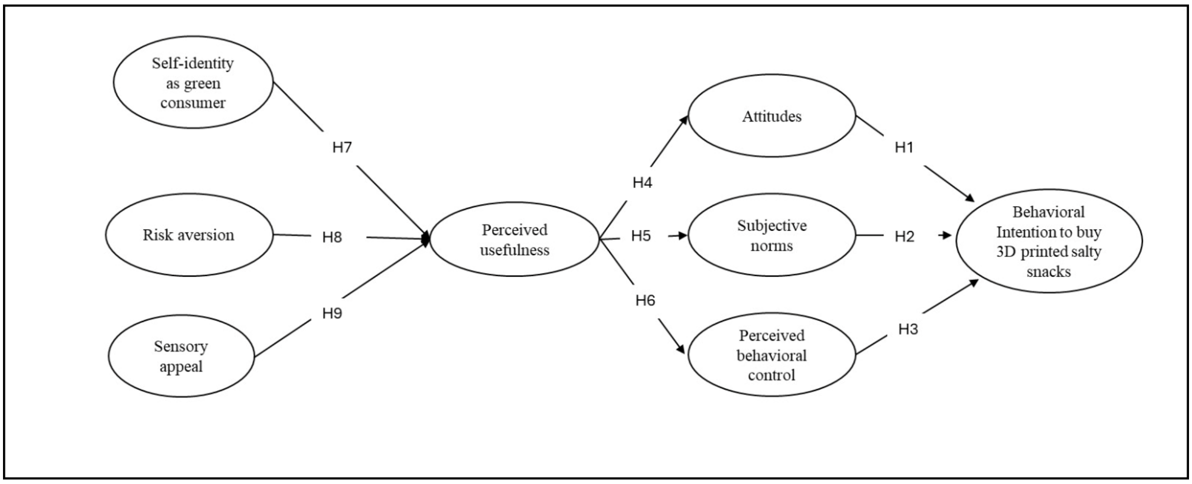

Figure 1. Theoretical model. H1. Attitude positively influences the behavioral intention to buy 3D-printed food. H2. Subjective norms positively influence the behavioral intention to buy 3D-printed food. H3. Perceived behavioral control positively influences the behavioral intention to buy 3D-printed food. H4. Perceived usefulness positively influences attitude towards purchasing 3D-printed food. H5. Perceived usefulness positively influences subjective norms towards purchasing 3D-printed food. H6. Perceived usefulness positively influences perceived behavioral control towards purchasing 3D-printed food. H7. Self-identity as a green consumer positively influences the perceived usefulness of 3D-printed food. H8. Risk aversion negatively influences the perceived usefulness of 3D-printed food. H9. Sensory appeal positively influences the perceived usefulness of 3D-printed food. Source: authors' elaboration.

3. Materials and Methods

Figure 2 illustrates the overall research design and analytical procedure of the study through a structured flowchart. It presents a sequential representation of the main stages, starting from the definition of the research objective and the development of the theoretical framework based on the extended TPB. The process continues with questionnaire design grounded in the literature, followed by data collection conducted through an online survey in Italy, and sample selection. The flowchart then outlines the analytical steps, including the assessment of the measurement model in terms of reliability and validity, the estimation of the structural model using PLS-SEM, and hypothesis testing. Finally, the sequence concludes with the interpretation of results and discussion.

In the following sections, the questionnaire design and the methodological approach adopted in this study are presented.

3.1. Questionnaire Description

To achieve the objectives of the study, a specific questionnaire was developed based on the relevant literature, respecting the principles of the Helsinki Declaration and the Italian Psychological Association ethical rules. To access the questionnaire, all participants had to explicitly agree with the provided informed consent, explaining about the purpose of the study, the voluntary nature of participation, data anonymity, confidentiality, and limited time storage. By selecting the "I agree to participate" option, respondents voluntarily provided their explicit consent, otherwise they were not allowed to continue with the survey. Participants were recruited through snowball sampling using the major social media (such as Facebook and WhatsApp) and online distribution channels (university mailing lists, and professional networks). The inclusion criteria were being: (i) resident in Italy; (ii) at least 18 years old; and (iii) consumers of savory snacks. Data were collected between July and August 2024 through the LimeSurvey platform (version 6.6.x), allowing for secure data collection and the automatic recording of responses in anonymous form.

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The questionnaire consisted of four sections and required, on average, eleven minutes to complete. The first section included screening questions to identify the target population, and compliance with the inclusion criteria. Age threshold was established to guarantee legal capacity to provide informed consent, while the consumption criterion ensured respondents' familiarity with the product category under investigation. The second section examined the purchasing and consumption habits of savory snacks, including questions about purchase frequency and place of purchase. The third section of the questionnaire, which represented its central part, focused on the TPB. Before introducing the measurement items, a short description of the 3D food printing was provided to respondents. Particularly, the Supplementary Material ("SEZIONE 2: descrizione stampa 3D degli alimenti e TPB") provides the description provided to respondents in the original language (Italian), and here follows its English translation:

"3D printing is a technique that enables the creation of three-dimensional objects by converting digital files into solid objects through the deposition of material in multiple layers. The application of this technology in the food sector enables the production of personalized foods to meet specific requirements regarding ingredients, quantity, calories, nutrients, shape, texture and flavor. By printing only the quantities required, food waste can be reduced, and selecting the appropriate ingredients can have beneficial effects on health".

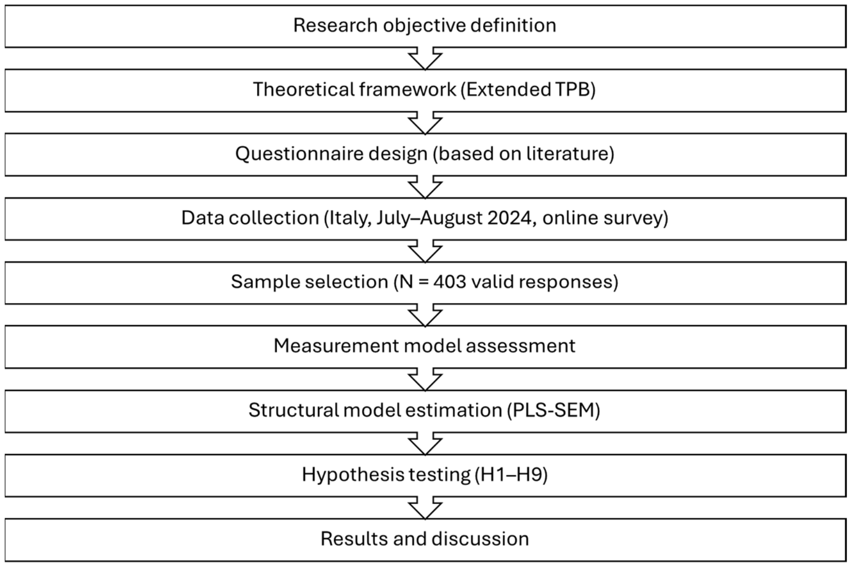

Figure 2. Research Design flowchart. Source: authors' elaboration.

Since all of the constructs were latent variables, validated measurement scales were adapted and applied in this study. All items were measured using a 7-point Likert scale, where 1 represents the maximum disagreement, and 7 the maximum agreement. The latent constructs and their measurement items are shown in Table 1, together with their references. Supplementary Material S1 reports the full questionnaire in the original language, while Supplementary Material S2 provides the English translation.

Section four collected information about previous knowledge of 3D food printing and consumer preferences towards these new food products.

Table 1. Latent Constructs and Measurement Items.

Constructs	Items	References
Behavioral intention to buy 3D-printed food.	I intend to purchase customized 3D-printed savory snacks in the next month, if available.	[42,56,58]
	I am planning to purchase customized 3D-printed savory snacks in the next month, if available.	
	I will purchase customized 3D-printed savory snacks in the next month, if available.	
	It would be important for me to find customized 3D-printed savory snacks in the next month, if available.	
	It would be important for me to consume customized 3D-printed savory snacks in the next month.	
Attitude	Purchasing customized 3D-printed savory snacks would be a bad/good choice.	[56,58–60]
	Purchasing customized 3D-printed savory snacks would be a harmful/healthy choice.	
	Purchasing customized 3D-printed savory snacks would be an unpleasant/pleasant choice.	
	Purchasing customized 3D-printed savory snacks would be an undesirable/desirable choice.	
	Purchasing customized 3D-printed savory snacks would be an impossible/possible choice.	
	Purchasing customized 3D-printed savory snacks would be a dissatisfying/satisfying choice.	
	Purchasing customized 3D-printed savory snacks would be a negative/positive choice.	
Subjective Norms	If personalized 3D-printed savory snacks were available, the people important to me would think that I should buy them.	[56,58,59]
	If personalized 3D-printed savory snacks were available, the people important to me would approve of me buying them.	
	If personalized 3D-printed savory snacks were available, the people important to me would want me to buy them.	
	If personalized 3D-printed savory snacks were available, I would feel social pressure to buy them.	
Perceived Behavioral Control	For me, it would be easy to purchase customized 3D-printed savory snacks.	[59]
	I am confident that if I wanted to, I could purchase customized 3D-printed savory snacks.	
	Whether or not I purchase customized 3D-printed savory snacks is entirely up to me.	
Perceived usefulness	I think 3D printers bring convenience.	[28]
	3D printers are a socially desirable technology.	
	I think 3D-printed foods are beneficial for people's health.	
	I think 3D-printed food products contribute to the development of the food industry.	
Self-Identity as Green Consumer	I consider myself an environmentally conscious consumer.	[56]
	I see myself as a person interested in sustainable/environmentally friendly consumption.	
	I consider myself a person who is very concerned about environmental issues.	

Table 1. *Cont.*

Constructs	Items	References
Risk Aversion	I am cautious about trying new or different products.	[57]
	I prefer to stick with a brand I usually buy rather than try something I am not sure about.	
	I never buy something unfamiliar if there is a risk of making a mistake.	
Sensory Appeal	It is important to me that the food I eat in a typical day has a good smell.	[61]
	It is important to me that the food I eat in a typical day looks appealing.	
	It is important to me that the food I eat in a typical day has a pleasant texture.	
	It is important to me that the food I eat in a typical day tastes good.	

3.2. Data Analysis Methods

Before conducting advanced analysis, the internal consistency of the measurement scales was assessed using Cronbach's alpha. In line with Hair and Alamer [57], values equal to or above 0.7 were considered suitable for scientific research.

Data was analyzed with Partial Least Squares Structural Equation Modeling (PLS-SEM), representing a versatile analytical technique particularly useful when research conditions impose constraints related to sample size, data distribution, or model complexity. Unlike covariance-based SEM, this method can be effectively applied to both large and small samples without requiring the assumption of multivariate normality [57]. Consequently, PLS-SEM is especially appropriate for exploratory analyses and empirical studies conducted in emerging or data-limited contexts, where such conditions are often encountered. Additionally, PLS-SEM has already been utilized in the literature to analyze data related to extended TPB applications [58]. Therefore, the PLS-SEM was preferred to other analysis methodologies.

Methodologically, PLS-SEM integrates two interrelated components: the measurement model, which specifies how observed indicators reflect their underlying latent constructs, and the structural model, which captures the hypothesized causal relationships among those latent constructs. The estimation process follows three main phases. First, latent variable scores are computed. Second, the quality of the measurement model is assessed. Finally, the structural model is evaluated to determine the strength and significance of the proposed relationships among constructs.

Model evaluation encompasses both reliability and validity criteria. Reliability is tested at multiple levels initially at the indicator level via outer loadings (ideally >0.70), and subsequently through internal consistency measures such as Cronbach's alpha and Composite Reliability (rhoc), which are considered acceptable for exploratory research when exceeding 0.60 [59]. Convergent validity is examined through the Average Variance Extracted (AVE), where values equal to or greater than 0.50 indicate satisfactory convergence. Additionally, to mitigate potential issues of common method bias, collinearity among constructs was assessed.

The structural relationships were then analyzed by inspecting the magnitude and statistical significance of the path coefficients [59,60]. Stability and significance were further verified through a non-parametric bootstrapping approach with 5000 resamples, which provided standard errors and t-values for hypothesis testing.

All analyses were performed using SmartPLS 4, which offers comprehensive functionalities for estimating, validating, and interpreting PLS-SEM models in complex behavioral and social science research frameworks.

4. Results

4.1. Descriptive Statistics

A total of 592 observations were collected; of these, 403 completed interviews were considered valid (68.1%), as 189 respondents (31.9%) were either under 18 years old, had never consumed savory snacks, or declined to participate.

Among the valid respondents, 48.88% was female, 35.96% male, 3.97% preferred not to answer, and 1.74% selected "none of the previous ones". Respondents' ages were categorized into six groups: 18–29 years; 30–39 years; 40–49 years; 50–59 years; 60–69 years; over 69 years. The results show that 55.08% of participants fall within the 30–49 years old groups, while 10.4% did not provide their age. Approximately half of the respondents (51.1%) held a university degree: fifty-two respondents (12.9%) had a specialization, PhD, or master's degree, ninety-one (22.6%) held a master's degree, and sixty-three (15.6%) a bachelor's degree. This aspect may reflect the greater tendency of more educated participants to respond to surveys.

Regarding purchasing and consumption habits, the results indicate that nearly 40% of respondents consumed savory snacks more than once a week, while most respondents (43.4%) were used to buying savory snacks one to three times per month. Regarding the places where savory snacks were purchased, the most common location was the supermarket (68.7%), followed at a distance by discount stores (11.4%) and hypermarkets (10.17%). Surprisingly, the frequency of purchasing savory snacks from vending machines was very low. Regarding knowledge of how 3D printers work, most respondents reported being familiar with their functioning. Focusing more specifically on the topic of this study and asking respondents whether they had heard of 3D food printing, 219 answered "Yes" (54.3%), 160 "No" (39.7%). The answers differed greatly when asking whether they had ever consumed 3D-printed food: here, only 22 respondents said "Yes" (5.46%), while 357 said "No" (88.6%). Indeed, it is not usual to find 3D-printed foods in conventional food stores.

Additionally, most of the respondents (53.6%) indicated that they would buy 3D-printed savory snacks only occasionally to try them, indicating an interesting consumer curiosity toward these products. Additionally, 28.6% of respondents would purchase 3D-printed savory snacks on special occasions or events, probably prioritizing the chance to personalize the snacks' shape, and only the 7.4% would consider daily consumption.

Respondents were also asked which consumer group 3D-printed savory snacks would be most suitable for, including children, elderly people with swallowing difficulties, adults with limited time for cooking, and athletes with specific nutritional needs. According to the sample, these products are considered less suitable for children and more suitable for athletes with particular requirements. Lastly, the survey revealed that more than half of the respondents (56.8%) would not be willing to pay a premium price for 3D-printed savory snacks with respect to the traditional ones. On the contrary, 24.8% would be willing to pay less than for traditional snacks.

Table 2 summarizes the characteristics of the sample. To respect respondents' sensitivity, given the nature of the questions, responses were not made mandatory. Consequently, missing values are present in the table.

Table 2. Characteristics of the sample.

Variable	Category	n	%
Gender	Female	197	48.88
	Male	145	35.96
	Prefer not to answer	16	3.97
	Other	7	1.74
	No answer	38	9.43
Age group (years)	18–29	45	11.17
	30–39	117	29.03
	40–49	105	26.05
	50–59	38	9.43
	60–69	29	7.20
	Over 69	27	6.70
	No answer	42	10.42
Education level	High school diploma	125	31.02
	Bachelor's degree	63	15.6
	Master's degree	91	22.59
	Postgraduate degree/PhD	52	12.9
	No answer	38	9.43
Frequency of savory snack consumption	More than once a week	160	39.7
	Once a week	145	35.98
	Once a month	77	19.11
	Once a year	21	5.21
Frequency of savory snack purchase	1–2 times per week	106	26.30
	1–3 times per month	175	43.42
	3–4 times per week	24	5.96
	5 times per week or more	7	1.74
	Less than once per month	91	22.58
Main place of purchase	Supermarket	277	68.7
	Discount store	46	11.4
	Hypermarket	41	10.17
	Vending machine	12	2.98
	Coffee bar	15	3.72
	Tobacco shops	3	0.74
	Other	7	1.74
Knowledge of 3D printing technology	Aware of how it works	241	59.80
	Not aware	138	34.24
	No answer	24	5.96
Heard about 3D food printing	Yes	219	54.3
	No	160	39.7
	No answer	24	5.96

Table 2. *Cont.*

Variable	Category	n	%
Ever consumed 3D-printed food	Yes	22	5.46
	No	357	88.59
	No answer	24	5.96
Intended occasion for buying 3D-printed snacks	Only occasionally/to try	216	53.6
	Special events	47	11.66
	Daily consumption	30	7.4
	In certain situations	68	16.87
	No answer	42	10.4
Preferred purchase place for 3D-printed snacks	Supermarket	192	47.6
	Specialized store	77	19.1
	Vending machine	62	15.4
	Pharmacy	13	3.2
	Other/no answer	59	14.7
Perceived suitable consumers for 3D-printed snacks	Athletes with specific needs	277	68.73
	Children	165	40.94
Willingness to pay	Same price as traditional snacks	229	56.8
	Lower price	100	24.8
	Higher price	48	11.9
	No answer	26	6.5
Food allergies/intolerances	No	274	67.99
	Yes	88	21.84
	No answer	41	10.17
Family food allergies/intolerances	No	247	61.29
	Yes	115	28.54
	No answer	41	10.17
Gastrointestinal diseases	No	297	73.7
	Yes	65	26.3
	No answer	41	10.17
Family gastrointestinal diseases	No	276	68.5
	Yes	86	21.34
	No answer	41	10.17

4.2. PLS-SEM Results

The measurement model was carefully tested to ensure its reliability and internal consistency. Items that displayed weak outer loadings or low Cronbach's alpha values were removed prior to the final estimation (PBC2 or RA1). Table 3 reports the psychometric results of the adjusted model. Overall, the constructs showed good reliability, with Cronbach's alpha values mostly above 0.70 and composite reliability (rhoc) values exceeding 0.80. ATT, SI, BI. SN, and SA achieved particularly high levels of internal consistency, as reflected by Cronbach's alpha and rhoc values greater than 0.90 and AVE scores well above the 0.50 threshold.

Table 3. Internal consistency for each construct.

Constructs	Codes	Mean	SD	Outer Loadings	AVE	CR (rho_c)	Cronbach's Alpha
Attitude (ATT)					0.84	0.97	0.97
	ATT1	3.28	1.91	0.91			
	ATT2	3.36	1.85	0.92			
	ATT3	3.48	1.97	0.94			
	ATT4	3.41	2.00	0.92			
	ATT5	3.59	2.01	0.86			
	ATT6	3.49	1.94	0.93			
	ATT7	3.60	1.97	0.94			
Self identity as green consumer (SI)					0.85	0.95	0.91
	SI1	4.51	1.82	0.91			
	SI2	4.85	1.80	0.93			
	SI3	4.53	1.81	0.92			
Behavioral intention (BI)					0.86	0.97	0.96
	BI1	2.87	2.05	0.92			
	BI2	2.79	1.97	0.95			
	BI3	2.69	1.95	0.94			
	BI4	2.91	2.04	0.92			
	BI5	2.63	1.93	0.92			
Perceived usefulness (PU)					0.75	0.92	0.89
	PU1	3.97	2.01	0.87			
	PU2	4.02	1.97	0.88			
	PU3	3.51	1.98	0.87			
	PU4	4.01	2.03	0.86			
Risk Aversion (RA)					0.61	0.74	0.78
	RA2	3.83	1.98	0.97			
	RA3	3.65	2.00	0.50			
Subjective Norms (SN)					0.83	0.94	0.90
	SN1	2.91	1.98	0.89			
	SN2	3.22	2.00	0.93			
	SN3	3.05	1.99	0.91			
Sensory Appeal (SA)					0.77	0.93	0.90
	SA1	5.61	1.49	0.89			
	SA2	5.37	1.64	0.93			
	SA3	5.61	1.40	0.91			
	SA4	6.07	1.34				
Perceived Behavioral Control (PBC)					0.68	0.81	0.55
	PBC1	3.28	2.00	0.92			
	PBC3	2.74	1.71	0.72			

PU also demonstrated strong convergent validity (AVE = 0.75) and internal reliability (Cronbach's alpha = 0.89; rhoc = 0.92). Conversely, RA exhibited weaker internal consistency (AVE = 0.61; Cronbach's alpha = 0.78), mainly due to one item (RA3) with a low outer loading (0.50). PBC showed moderate reliability (AVE = 0.68; ρc = 0.81) but a relatively low Cronbach's alpha (0.55), which is likely influenced by the limited number of retained indicators. Although this value falls below the commonly accepted threshold, Cronbach's alpha should not be interpreted rigidly, as it is sensitive to the number of items and may underestimate internal consistency, particularly in short scales or complex constructs [62]. Accordingly, previous research has reported acceptable values even below 0.60, especially in exploratory research contexts. However, the relatively low Cronbach's alpha suggests limited internal consistency, which may affect the stability of the estimates related to PBC and therefore calls for caution in interpreting its role within the structural model. In general, the measurement model demonstrated satisfactory reliability and convergent validity, supporting the robustness of the final constructs.

Discriminant validity was examined through the inter-construct correlation matrix presented in Table 4. The results indicate that the constructs are generally distinct, although some strong relationships were observed. ATT exhibited high correlations with PBC (=0.93), PU (=0.88), and SN (=0.76), suggesting that favorable attitudes toward green consumption are closely associated with perceived control, perceived utility, and normative influence. Similarly, BI was strongly correlated with PBC (0.83) and moderately with PU (0.71) and SN (0.71), implying that intention is shaped by both cognitive evaluations and social pressures.

Table 4. Discriminant validity.

	ATT	BI	PBC	PU	RA	SI	SA	SN
ATT								
BI	0.797							
PBC	0.925	0.829						
PU	0.882	0.714	0.933					
RA	0.101	0.062	0.041	0.093				
SI	0.357	0.264	0.489	0.456	0.095			
SA	0.156	0.052	0.192	0.171	0.186	0.274		
SN	0.757	0.709	0.735	0.729	0.064	0.229	0.056	

SI showed moderate relationships with PBC (0.49) and PU (0.46), highlighting its relevance to individuals' perceived ability and belief in the usefulness of pro-environmental behaviors. SA presented low-to-moderate correlations with the other constructs, consistent with its distinct experiential nature. In contrast, RA displayed very weak correlations with all other variables (ranging from 0.04 to 0.19), indicating that perceived risk plays a relatively independent role within the model.

Despite some high pairwise associations—particularly between ATT, PBC, and PU—the Fornell–Larcker criterion was satisfied, as the square roots of the AVE values for each construct exceeded their corresponding inter-construct correlations. These findings confirm adequate discriminant validity and support the distinctiveness of the latent constructs in the final measurement model.

Multicollinearity was assessed using the variance inflation factor (VIF) values (Table 5). All indicators reported VIF values well below the critical threshold of 5.0, indicating the absence of problematic collinearity among the constructs. Specifically, Attitude (VIF = 2.857) and PBC (VIF = 2.070) showed the highest but still acceptable levels, suggesting a moderate association with related predictors. SN (VIF = 2.037) also remained within the recommended range, confirming that multicollinearity does not pose a concern.

Table 5. VIF analysis.

	ATT	BI	PBC	PU	RA	SI	SA	SN
ATT		2.857						
BI								
PBC		2.070						
PU	1.000		1.000					1.000
RA				1.034				
SI				1.072				
SA				1.107				
SN		2.037						

All other constructs—PU (VIF = 1.000), RA (VIF = 1.034), SI (VIF = 1.072), and SA (VIF = 1.107)—demonstrated very low VIF values, indicating minimal shared variance with other predictors. Overall, the results confirm that collinearity among the exogenous variables is not an issue, and the model satisfies the assumptions for subsequent structural analysis.

To further explore the potential presence of curvilinear associations among the constructs, quadratic terms (QEs) were added to the structural model. The analysis revealed several noteworthy nonlinear effects (Table 6). Among them, ATT showed a significant positive quadratic influence on BI (β = 0.196, $p < 0.001$), indicating that higher levels of attitude intensify the intention to engage in the behavior. In contrast, SN exhibited a significant negative quadratic effect on BI (β = −0.182, $p < 0.001$), suggesting that the contribution of SN to behavioral intention tends to plateau or even decline beyond moderate levels.

Table 6. Assessing of quadratic effects.

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (∣O/STDEV∣)	*p* Values
QE (ATT) → BI	0.196	0.193	0.039	5.001	0.000
QE (PBC) → BI	0.025	0.027	0.039	0.628	0.530
QE (PERCEIVED USEFULNESS) → ATT	0.034	0.033	0.026	1.320	0.187
QE (PERCEIVED USEFULNESS) → PBC	−0.018	−0.018	0.034	0.539	0.590
QE (PERCEIVED USEFULNESS) → SUBJECTIVE NORMS	−0.024	−0.024	0.040	0.603	0.546
QE (RISK AVERSION) → PERCEIVED USEFULNESS	0.008	0.005	0.059	0.130	0.896
QE (SELF IDENTITY) → PERCEIVED USEFULNESS	−0.136	−0.137	0.048	2.807	0.005
QE (SENSORY APPEAL) → PERCEIVED USEFULNESS	−0.000	0.009	0.032	0.009	0.993
QE (SUBJECTIVE NORMS) → BI	−0.182	−0.182	0.045	4.006	0.000

A further significant nonlinear relationship emerged for SI, which displayed a negative quadratic effect on PU (β = −0.136, $p = 0.005$). This implies that while a stronger ecological self-identity initially enhances perceptions of usefulness, its marginal effect decreases at higher identity levels. The remaining quadratic effects—those involving PBC, PU, RA, and SA—were not statistically significant ($p > 0.05$), indicating linear relationships in those cases.

Overall, these findings suggest that nonlinear dynamics are present in the model, particularly for ATT, SN, and SI, highlighting the complex nature of behavioral drivers within the green consumer framework.

Table 7 presents the results of the structural model estimated through the PLS-SEM procedure, comparing both the linear and nonlinear specifications. The analysis aimed to assess the significance and direction of the hypothesized relationships among the key psychological and perceptual constructs influencing BI toward sustainable or pro-environmental actions.

Table 7. PLS-SEM results.

	Coefficients			
Path	**Linear Model**		**Nonlinear Model**	
ATT → BI	0.49	***	0.44	***
PBC → BI	0.18	***	0.16	***
PU → ATT	0.82	***	0.82	***
PU → PBC	0.68	***	0.68	***
PU → SN	0.66	***	0.66	***
RA → PU	−0.14		−0.13	
SI → PU	0.40	***	0.34	***
SA → PU	0.09	**	0.08	**
SN → BI	0.21	***	0.32	***
QE (ATT) → BI	-		0.21	***
QE (SI) → PU	-		−0.13	**
QE (SN) → BI	-		−0.18	***
R^2				
BI	0.63		0.67	
BIC				
BI	−382.294		−408.368	

Note: Statistical significance is indicated as follows: ** $p < 0.01$, *** $p < 0.001$.

The findings indicate that the relationships posited in the theoretical model are largely significant and aligned with expectations. In particular, ATT exerts a strong and positive influence on BI ($\beta = 0.49$, $p < 0.001$ in the linear model; $\beta = 0.44$, $p < 0.001$ in the nonlinear model), confirming its central role as a determinant of intention. Similarly, PBC positively affects BI ($\beta = 0.18$, $p < 0.001$; $\beta = 0.16$, $p < 0.001$), underscoring the importance of perceived autonomy and ability in shaping individuals' behavioral choices. SN also has a significant and positive effect on BI, which becomes stronger in the nonlinear specification ($\beta = 0.21$, $p < 0.001$; $\beta = 0.32$, $p < 0.001$), suggesting that social influence intensifies beyond moderate levels of normative pressure.

PU emerges as a pivotal construct in the model, positively influencing ATT ($\beta = 0.82$, $p < 0.001$), PBC ($\beta = 0.68$, $p < 0.001$), and SN ($\beta = 0.66$, $p < 0.001$). Among its antecedents, SI shows a significant positive effect on PU ($\beta = 0.40$, $p < 0.001$; $\beta = 0.34$, $p < 0.001$), while SA contributes more modestly but still significantly ($\beta = 0.09$, $p < 0.01$; $\beta = 0.08$, $p < 0.01$). RA, in contrast, displays a negative but non-significant path toward PU ($\beta = -0.14$; $\beta = -0.13$), indicating a limited role in shaping PU.

When quadratic effects are introduced, several nonlinear patterns emerge. The inclusion of quadratic terms reveals a positive and significant curvilinear effect of ATT on BI ($\beta = 0.21$, $p < 0.001$), suggesting that stronger attitudes amplify intention once a certain threshold is reached. Conversely, SI shows a negative quadratic relationship with

PU ($\beta = -0.13$, $p < 0.01$), implying the diminishing returns of identity salience on PU at higher levels. SN also displays a negative quadratic effect on BI ($\beta = -0.18$, $p < 0.001$), indicating that excessive normative influence may eventually reduce intention, possibly due to perceived social pressure or conformity fatigue.

The nonlinear model exhibits an improved explanatory capacity, with the explained variance for BI increasing from $R^2 = 0.63$ in the linear model to $R^2 = 0.67$ in the nonlinear one. Moreover, the BIC value decreases substantially (from −382.29 to −408.37), confirming that the inclusion of quadratic terms enhances model fit and provides a more accurate representation of the complex relationships among the constructs.

5. Discussion

By investigating consumer intention toward 3D-printed savory snacks, this study offers valuable insights into the evolving field of sustainable purchasing behavior. The findings indicate that attitude and subjective norms play a central role in influencing behavioral intention to buy 3D-printed savory snacks. More specifically, attitude, which reflects how positively or negatively a person views the behavior, emerges as the strongest driver of behavioral intention, followed by the influence of social expectations from family, friends, and close others (i.e., subjective norms). These results confirm hypotheses H1 and H2 and are consistent with previous studies on novel food acceptance, which emphasize the importance of favorable attitudes and social pressure in guiding consumer choices toward emerging technologies [8,51].

On the other hand, hypotheses H3 and H6 were confirmed despite the low value of factors loading of perceived behavioral control. Although unexpected, this outcome is consistent with literature on acceptance and intention to consume 3D-printed food [51]. This aspect could be related to the fact that perceived behavioral control may not be reliable in contexts where a real market for the product does not yet exist. Since this construct evaluates the perceived ability to perform a behavior, its instability indicates that further investigation will be needed once 3D-printed food becomes more accessible to consumers on the conventional food markets. In this case, as suggested by Stranieri [42], it would also be possible to analyze the actual behavior, which is not possible to measure for products not-available on food markets.

Hypothesis H7 is confirmed, as consumers with relevant levels of self-identity as green consumer are more likely to recognize the ecological and social benefits of 3D food printing, including waste reduction and the valorization of by-products. This finding is consistent with Carfora et al. [56], who highlighted the role of green self-identity in shaping sustainable food consumption behaviors.

Hypothesis H8 is not confirmed, as risk aversion shows a not-statistically significant association with perceived usefulness. This is surprising given that previous literature found consumers have concerns related to the safety of 3D-printed foods [63].

Hypothesis H9 is supported: Sensory appeal is rated highly by consumers and directly influences perceived usefulness. This may suggest that consumers associate sensory characteristics with 3D-printed snacks, despite not having experienced them so far.

Lastly, hypotheses H4 and H5 are confirmed. Perceived usefulness proves to be crucial, positively influencing both attitude and subjective norms, as expected considering previous literature [64]. This suggests that the belief that 3D printing can generate tangible benefits is central to shaping consumers' behavioral intention.

Table 8 provides a summary of the hypotheses tested in this study, indicating which were confirmed, or not.

Table 8. Summary of the hypotheses tested.

Hypothesis	Relationship	Result
H1	Attitude → Behavioral intention to buy 3D-printed food	Confirmed
H2	Subjective norms → Behavioral intention to buy 3D-printed food	Confirmed
H3	Perceived behavioral control → Behavioral intention to buy 3D-printed food	Confirmed
H4	Perceived usefulness → Attitude	Confirmed
H5	Perceived usefulness → Subjective norms	Confirmed
H6	Perceived usefulness → Perceived behavioral control	Confirmed
H7	Self-Identity as Green Consumer → Perceived usefulness	Confirmed
H8	Risk Aversion → Perceived usefulness	Not confirmed
H9	Sensory Appeal → Perceived usefulness	Confirmed

These results are particularly interesting given that the agrifood sector requires a shift from traditional structural models to more sustainable ones because it is responsible for a significant part of global greenhouse gas emissions within the entire production cycle [2]. In addition, the increasing global population, combined with changes in consumption behavior, puts more pressure on natural resources, increasing concerns about the environmental footprint of agriculture [3]. Nevertheless, the agrifood sector represents a key driver capable of enhancing the achievement of a sustainable shift by implementing innovative practices, adopting low-impact technologies, and developing more flexible supply chains.

Keeping these ideas in mind, the agricultural sector is placed at the center of many policy initiatives. For example, in 2020, the European Commission published the Farm to Fork (F2F) strategy whose goal was to steer the agricultural system towards sustainability [63,64]. Furthermore, in February 2025, the "Vision for Agriculture and Food" established a long-term vision extending until 2040, not just to reduce environmental footprints but also to make territories more attractive, competitive, responsive, and fair, and to better link citizens, rural areas, and the environment. To achieve this, the policy brings together a range of actions: biodiversity conservation, animal welfare, fair competition, and encouraging the adoption of emerging technologies to develop digital skills [7].

Particularly, emerging technologies are a potential driver of competition, marginal areas resilience and sustainable productions. In examining the role of innovation in the agrifood sector, it is pivotal to investigating not only the supply side, but also the demand side. On the supply side, firms are subject to a series of external pressures that force them to enhance the sustainability of the agrifood sector at both the macro and micro levels. At the macro level, there are programs such as the European Union's Horizon 2020 Framework Program for Research and Innovation and the United Nations' Sustainable Development Goals that emphasize investing in research and innovation to achieve food security as well as promote sustainable agriculture [8,11]. These initiatives assign firms a central role in positively impacting public health and the environment by making efforts to improve the nutritional quality of food products. At the firm-level scale, growing global competition and the continuous need to remain competitive increasingly pressure agrifood firms, demanding significant efforts to innovate and adapt to market requirements.

Among emerging innovations in the agrifood sector, novel foods represent a particularly promising area, including 3D-printed foods, insect-based products, and lab-grown meat [15]. Particularly, 3D food printing can use dough based on insect or lab grown meat, which are both considered as sustainable innovations [15]. These alternatives, indeed, offer potential solutions to environmental challenges by reducing greenhouse gas emissions, optimizing the use of resources, and minimizing the loss of food [65]. Insect foods provide high-quality protein with less environmental impact than conventional meat. Moreover, cultured meat is consistent with sustainability as well as improved animal welfare. In addition, 3D-printed foods can increase efficiency within the whole food supply chain, from production to storage and transportation, by reducing food loss and using by-products [14]. In this context, promoting the adoption of innovative food technologies is essential to support the transition toward more sustainable agrifood systems. Particular attention should be paid to younger consumers, as previous studies have shown that they tend to exhibit higher acceptance of 3D-printed foods compared to older individuals (e.g., [65]). Accordingly, recent research has increasingly focused on the role of younger generations in shaping the adoption of such innovations [66]. On the one hand, younger individuals often exhibit less balanced dietary habits due to time and financial constraints, making them a relevant target for technologies that can provide convenient and nutritionally adequate food solutions [67]. On the other hand, they tend to be more sensitive to sustainability issues and more open to technological innovation, reinforcing their importance as a key segment for the diffusion of 3D-printed foods. So that, understanding the determinants of consumer acceptance is crucial for identifying the factors and strategies that can support the successful market adoption of 3D-printed food products.

6. Conclusions

The purpose of this study was to examine the potential market for 3D-printed sustainable food products by analyzing psychological constructs that can affect consumer intention. To this aim, the paper focused on Italian consumer intentions to buy 3D-printed savory snacks as a case study. Proposing an extended TPB model, the study highlighted that attitude and subjective norms are the major drivers of behavioral intention, while perceived usefulness affects both attitude and subjective norms. Additionally, self-identity as a green consumer and sensory appeal were confirmed as relevant factors, while no effect was shown for risk aversion.

Based on these results, consumers' purchasing intention for 3D-printed foods can be encouraged by using several strategies. Firstly, policymakers and firms must emphasize the tangible benefits of 3D-printed foods like sustainability, healthiness, and the efficient use of by-products to promote positive attitudes and perceived usefulness. Secondly, firms and researchers should focus on improving the ability of 3D food printing technology to provide the above-mentioned benefits. Thirdly, awareness and knowledge about new food can increase consumers' sensory appeal towards these new foods and increase the power of subjective norms; therefore, these products may be promoted by using focused education, and with advertising efforts. Indeed, as these products are fully customizable they retain the potential to exert a high sensory appeal.

Finally, at the policy level, programs like incentives for digital innovation, environmental certifications, and the diffusion of 3D food printing into broader sustainability programs can improve trust, perceived usefulness, and overall acceptance intention, enabling the sustainable development of the agrifood industry.

This study could have several important implications. First, from the methodological perspective, it proposes an extension of the Theory of Planned Behavior (TPB), contributing to a deeper understanding of the psychological factors that influence consumer behavior. Additionally, by focusing on the Italian context—still relatively underexplored in this field—it helps fill a gap in the literature and shed light on a consumer group that has received limited attention so far whilst being interesting to analyze considering its strong culinary traditions. The findings also provide valuable insights for policymakers, offering guidance for the development of strategies and interventions aimed at promoting more sustainable and innovative food consumption practices. Finally, businesses could use these findings to assess whether investments in digitalization and 3D food printing represent a strategic opportunity to tap into new market niches and enhance their competitiveness.

Despite the contribution of this study, some limitations should be acknowledged and addressed in future research. The sample was limited to Italian consumers, and it was not representative of the population, which could limit the generalizability of findings. Therefore, descriptive estimates should not be interpreted as population-level parameters. However, since the study primarily aims to examine associations and behavioral mechanisms among constructs/variables (rather than to estimate prevalences or population-level absolute values), the use of a non-probability sample is consistent with the study's analytical objective. Accordingly, the findings should be interpreted mainly in terms of the pattern, direction, and structure of the relationships observed among the study variables. In addition, some constructions with low internal validity require further investigation, so that future research can integrate additional psychological and relevant factors beyond the TPB framework, including sensory evaluation, economic ideas and other social impacts to provide a wider understanding of consumer acceptance. Moreover, to better understand consumer intention towards these products, the study should be repeated once 3D printed food is available on the market. Lastly, considering different case studies may lead to different results; therefore it would be interesting to compare the acceptance of several 3D-printed products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18083874/s1, S1: Italian (original language) version of the questionnaire, S2: English translation of the questionnaire.

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Institutional Review Board Statement: This study is waived for ethical review as the survey was completely anonymous, collected no sensitive or identifying personal data, each participant voluntarily chose to take part in the study and was allowed to interrupt the survey at any time. Data were collected anonymously and processed in compliance with EU Regulation 2016/679, stored only for the time necessary to achieve research objectives, and presented in aggregated form to avoid any possible identification. The study was conducted in accordance with the Declaration of Helsinki (1975, revised in 2013) and the Italian Psychological Association ethical rules.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Abbreviations

The following abbreviations are used in this manuscript:

TPB	Theory of Planned Behavior
ATT	Attitude
SI	Self identity as green consumer
BI	Behavioral intention
PU	Perceived usefulness
RA	Risk Aversion
SN	Subjective Norms
SA	Sensory Appeal
PBC	Perceived Behavioral Control
QE	Quadratic effects

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