Global perceptions and acceptance of irradiated food: a comparative systematic review

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Abstract

Irradiated food acceptance around the world exhibits systematic variabilities across many facets related to citizens' perceived approval ratings of the product. The present research summarizes the empirical evidence on the extent to which people around the world accept irradiated food. A systematic review methodology structured the design and implementation of the present analysis. The authors performed comprehensive searches for studies featuring acceptance rates in two broad databases: Web of Science and Scopus. A total of 27 peer-reviewed articles in the English language covering 24,474 people in 15 different countries provided the survey-based data for the investigation. Results indicated that acceptance of irradiated food increased by a large margin in the past 35 years (33% in 1992 to 67% in 2024). Citizens' refusal to purchase irradiated food decreased from 19% to 16% globally in the same period. One of the emerging trends in the results was the rate of irradiated food familiarity, which remained relatively unchanged at 50% in the same time frame. Globally, acceptance of irradiated food is high and rising. Information campaigns and education about the benefits of irradiated food have led to increases in awareness and familiarity. Despite improving perceptions globally, stark variability still exists in acceptance rates, with developing countries having lower acceptance compared to highly industrialized countries. This is the first comparative analysis of different populations' perceptions of irradiated food worldwide. The paper provides new estimates on global acceptance of irradiated food and highlights variability among countries, offering valuable insights for policymakers interested in investing in it.

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Introduction

Food irradiation is a process that uses ionizing radiation to kill bacteria, viruses, and other pathogens in food, helping to extend its shelf life and reduce the risk of foodborne illnesses (United States Food and Drug Administration, 2021). This process does not make the food radioactive; it is similar to pasteurizing milk or canning vegetables to make them safer and last longer. The potent ability of irradiation to eliminate harmful causes of illnesses like *Salmonella* and *Escherichia coli* at rates exceeding 99% presents an opportunity for improving the adoption and refinement of the technology (Farkas, 2006; Szczawińska, 2017). Irradiation prolongs the shelf life of products without altering their main nutritional value (Prakash, 2016). For instance, berries' normal shelf life is about 1 week, and with irradiation, that period is extended to 3 weeks (D'Souza *et al*., 2021). Food irradiation is capable of reducing waste; currently, food waste is as high as 40% across many jurisdictions around the world, and the implementation of irradiation significantly helps mitigate the problem (Watanabe and Kawata, 2017). The primary research problem motivating the present review is the absence of systematic reviews on consumers' acceptance, awareness, familiarity, and purchasing intent of irradiated food. Despite the plethora of surveys on consumers' attitudes toward irradiated food, none of the published research reported common trends and patterns defining consumers' behaviors on a global scale. Exciting studies fail to document stark variability in acceptance or awareness among consumers across different geographic regions around the world (Farkas, 2006; Galati *et al*., 2019; Mshelia *et al*., 2023). Examining consumers' acceptance of irradiated food uncovers prevalent myths and misconceptions among a certain population, allowing stakeholders the knowledge to design appropriate education and awareness campaigns or pro-

grams to address misinformation (D'Souza *et al*., 2021; Nguyen *et al*., 2021). Learning about consumers' willingness to purchase irradiated food informs the government and the private sector on the potential success of investing in the implementation and refinement of the technology and the food products affected by the sector (Maherani *et al*., 2016; Fernandes *et al*., 2018). Consumer preferences alter public policies and regulations; thus, surveying consumers in specific markets allows researchers to understand the causes or motivations for the facilitation or hindering of technology adoption (Eustice and Bruhn, 2012; Nguyen *et al*., 2021).

The purpose of this research is to synthesize the survey literature concerning consumers' acceptance, awareness, familiarity, and purchasing intent of irradiated food around the world. By the same token, this research aims to present a global perspective on how ordinary citizens perceive irradiated food despite geographic and demographic variability. The guiding research question for the analysis is to what extent do people around the world accept irradiated food as a viable product in the marketplace? Relatedly, the study inquires into what degree people around the world are aware of irradiated food and intend to purchase it. Answering such questions provides researchers with a comparative perspective on citizens' perceptions of irradiated food, incorporating samples from all continents with available research.

This research assessed 27 peer-reviewed articles published by 21 journals between 1992 and 2024. The total number of surveyed individuals was 24,474 in 15 countries. On average, 54% of all surveyed individuals around the world expressed their acceptance of irradiated food. Acceptance rates increased from 33% in 1992 to 67% in 2024. Despite the noticeable gains in acceptance, awareness of irradiated food is still relatively low. Familiarity with irradiated food labels has remained moderate during the past three decades, with a slight increase from 50% in 1995 to 53% in 2023. While much of the research published utilized non-probability samples, the current research notes the power of education in increasing acceptance and awareness levels among consumers. Despite the growing interest in addressing myths concerning irradiated food, uncertainty among many is still real, and food safety concerns constitute the largest proportion of such uncertainty.

Literature review

Familiarity and awareness

Past researchers have examined the familiarity and awareness levels of the public concerning food irradiation. Nguyen *et al*. (2021) surveyed the literature on food irradiation knowledge. Only 19% (21) out of the total 93 studies reviewed by the authors explicitly dealt with consumers' knowledge. In the US, consumers' knowledge of irradiated food increased from 23% to 49% in 2007 (Bhumiratana *et al*., 2007). Across developing countries, familiarity with irradiated foods is low (Nguyen *et al*., 2021). In Argentina, Flores and Hough (2008) concluded that 79% of the participants in their study did not partake in any education or training featuring food irradiation, leading to limited knowledge levels concerning the technology. A survey of 497 individuals from Chile indicated that three-quarters of the sample were unaware of irradiation as a strategy for food preservation (Junqueira-Gonçalves *et al*., 2011). In the same study, the authors concluded that 91% of the sample would consume irradiated food if they knew that irradiation is not tantamount to radioactivity. Jankuloski *et al*. (2022) surveyed Macedonian awareness and willingness to purchase ionized irradiated food. The survey included 92 individuals from two high schools, featuring teachers, students, and employees. Results suggested a low willingness to buy irradiated food, with 8.7% (8 individuals) in the sample demonstrating their intent to purchase such food. Most importantly, approximately 96% of all surveyed people suggested non-familiarity with irradiation food labels like "Radura", which is used in Chile (Junqueira-Gonçalves *et al*., 2011). In sum, people around the globe are still wary about irradiated food. The willingness to consume irradiated food is meager among people around the world. A large proportion of food irradiation consumers' acceptance investigated their perceptions or attitudes [75% of a total of 93 studies in a review by Nguyen *et al*. (2021)]. Consumer attitudes toward irradiated foods were largely negative in the 1980s (Nguyen *et al*., 2021). Surveys indicated that 20-25% of individuals were willing to purchase irradiated food and held positive views about it in the 1980s. With the increased volume of information about the benefits and safety of irradiated foods, the proportions of individuals in surveys investigating their perceptions of the technology improved, reaching about 50% in the early 2000s (Nguyen *et al*., 2021).

The purposeful marketing of irradiated foods as healthy, safe, and nutritious increased the percentage of individuals exhibiting positive opinions of such food in the past two decades by 60% across many countries around the world (Nguyen *et al*., 2021). About half of the sample in Junqueira-Gonçalves *et al.* (2011) study indicated their willingness to purchase irradiated food, signaling their perceived trust in the labels. In a similar study conducted in Macedonia by Jankuloski *et al*. (2022), the researchers reported a low familiarity and acceptance rate among the sample of 92 individuals. 71.7% (66 individuals) suggested that irradiated food is of inferior quality compared to food processed with preservatives. Additionally, 75% of the sample (69 individuals) suggested that they are not aware of whether irradiated food causes cancer or not. Conclusively, consumers required further information about irradiated food to construct a positive attitude.

Factors affecting consumers' acceptance

Information constitutes one of the most important factors influencing people's decision to consume irradiated food. Bruhn (1998) suggested that when scientifically based information is provided to consumers regarding the benefits of food irradiation, 60-90% of individuals become willing to consume such products. Further, the author stated that 99% of consumers transform their negative or skeptical attitudes toward irradiation when presented with information accompanied by specific samples of irradiated food items (Behrens *et al*., 2015). Bruhn (1998) concluded that consumers are willing to shift negative opinions on food irradiation, turning them into positive perceptions when presented with scientifically based information (Behrens *et al*., 2015). For instance, the information should communicate the product benefits, as well as its safe consumption. Further, information on food irradiation should address the wholesomeness of products, their environmental impact, and institutional as well as authoritative endorsements. In a related study, Galati *et al*. (2019) concluded that when Italians are well-informed about the myths of irradiated food, they become more willing to purchase it. All in all, information campaigns concerning irradiated food help in shifting public opinion.

Risk, fear, and worry represent a collection of perceptions that prevent people from consuming irradiated food. Galati *et al.* (2019) examined Italian consumers' acceptance of irradiated food. Using an online survey of 392 individuals, the authors performed a Probit Regression, estimating the probability of acceptance. Results indicated that perceived risk has the greatest influence on

acceptability. More specifically, consumers who believe that irradiation causes radioactivity that carries negative health effects after consumption resist the purchase of irradiated food. Demographic factors also influence the acceptability of food irradiation consumption among Italians. Older individuals are less likely to accept irradiated food compared to younger Italians. Further, consumers residing in food-producing communities like Southern Italy are less likely to accept the consumption of irradiated food compared to Northern Italy. Additionally, high-income households are more likely to accept the purchase and consumption of irradiated food in Italy (Galati *et al*., 2019).

Misconceptions

Misconceptions surrounding irradiated foods often lead to hesitancy and resistance among consumers. One of the most common misconceptions about food irradiation is its alleged connection to cancer (Nayga *et al*., 2005; Watanabe and Kawata, 2017; Withworth *et al*., 2017). In many studies, consumers voiced concerns over the ability of irradiation to damage their health (Castell-Perez and Moreira, 2021). The word irradiation echoes radioactivity or radiotherapy in the psyches of many consumers, recalling cancer, making them hesitant to accept the consumption of irradiated food. Studies demonstrated that the resulting amount of 2-dodecylcyclobutanone from irradiation is too small to harm people's health (WHO, 2003; Watanabe and Kawata, 2017). Similarly, safety appraisals showed that the amount of new compounds appearing in food items after irradiation is of no significant harm to human health (Feliciano, 2018; Fernandes *et al*., 2018). Consumers think good hygiene in food processing would eliminate the need for irradiation. But cross-contamination risks, especially in fresh produce, require intervention like irradiation. Fresh produce caused many recent foodborne illness outbreaks globally (CDC, 2018). However, consumers misunderstand irradiation as a fix for poor production practices, reflecting distrust in both technology and the industry. There are other misconceptions prevalent among consumers, especially regarding nutritional value. Irradiated foods do not have lower nutritional value compared with other processed foods (Prakash, 2020). Like all processing methods, irradiation affects nutrients similarly to other techniques. It even preserves nutrients better than some thermal processes (Prakash, 2020), with minimal impact on taste and sensory qualities (Loaharanu, 2003; Fernandes *et al*., 2018). However, despite the nutritional advantages and sensory preservation offered by irradiation, many consumers still harbor misconceptions about the cost and benefits, perceiving it as expensive and primarily advantageous to the food industry, which impedes wider acceptance (DeRuiter and Dwyer, 2002). Many consumers mistakenly believe irradiated foods are costly and only benefit the food industry (Daly, 1989; Deliza *et al*., 2010). They do not see personal benefits like longer shelf life and delayed fruit ripening. This perception leads them to resist paying extra for irradiated products. Mistrust in the industry and fears similar to those about genetically modified organisms also contribute to low acceptance (Siegrist *et al*., 2003; Siegrist, 2008). By addressing these misconceptions, there is potential to build trust and acceptance towards irradiation as a necessary food safety measure.

Methodology

Eligibility criteria

The eligibility criteria for this research included the presence of statistics on irradiated food consumption, acceptance, awareness, and familiarity within a sample of individuals surveyed in published literature. The statistics needed to be relative frequencies, frequencies, or percentages demonstrating the number or proportion of people expressing their perceptions regarding irradiated food. Alternatively, studies containing mean values were included after the central tendency statistics were converted into relative frequencies. Studies needed to feature a sample of people and a survey or questionnaire on the extent to which people are willing to purchase or consume irradiated food. Note that not all included studies provided the full list of items on their questionnaires or details concerning their sampling strategies or population. They, however, all provided specific statistics on individuals' perceptions concerning irradiated food.

The inclusion criteria featured peer-reviewed, published articles in English. The search included studies since 1990 to allow readers to evaluate changes in perceptions over time. The quality of journals was not a concern; therefore, all studies featuring a sample of individuals surveyed on irradiated food constituted eligible papers for inclusion. The journal's impact factor information was recorded to indicate some level of quality to assess the included papers.

Information sources

Two databases provided the articles needed to complete this research: Web of Science and Scopus. Both databases include many relevant journal-published papers on irradiated food perceptions. Each database features different journals that potentially constitute good choices for publishing on the topic. They include an interdisciplinary collection of journals spanning a plethora of fields and research areas. The searches in each database were completed independently during the same time frame for conducting this research. All searches were completed in March 2024. Within each search session, the same keywords or phrases were inserted into search engines, and the number of studies found was logged. Further, the inspection of eligible studies was conducted immediately following each search.

Search strategy

The search strategy began with the insertion of a few combinations of keywords into the search engines of the databases. Each combination was conducted on its own. The combinations were: irradiated food and consumer acceptance, irradiated food and consumer awareness, irradiated food and consumer familiarity, and irradiated food and consumer intent. Each search generated unique results. Every result was logged, and a listing of articles for each of the searches was prepared. *Supplementary Figure 1* demonstrates the selection process for the studies included in this research.

Selection process

The selection of studies was based on a meticulous process conducted by the two researchers together. First, each listed article was evaluated using its title and abstract. Once the article was deemed appropriate for the study, a full review of its contents was done by the two researchers in the same session. The authors looked for specific statistics in the paper's results section, locating

frequencies and relative frequencies to construct percentages. All articles that did not include explicit statistics were removed from the list. The content review of the selected articles after inclusion based on the title and abstract followed systematic steps. First, the two authors visited the results or findings sections of included papers searching for relative frequencies, proportions, or means on survey items concerning irradiated food perceptions. Second, once the items were located by the authors, they went through a classification process to determine the variable being measured at hand. For every paper, the authors designated one item or a value on a construct to operationalize variables of interest, including awareness, familiarity, safety, intent to buy or not to purchase, and uncertainty or safety concerns. Third, the authors revisited the classification to ensure agreement prior to the estimation of percentages to increase the reliability and accuracy of selection. Note that each paper featured different survey instruments; the authors needed to establish agreement on items for each study separately. If studies did not feature clear-cut items concerning the variables of interest, they were excluded.

Data collection process

The data items selected for this research were consumers' acceptance, awareness, familiarity, and intent to purchase irradiated food. Acceptance refers to the extent to which consumers believe that irradiated food is a viable option for safe consumption in the marketplace. Awareness refers to the knowledge levels of consumers with respect to irradiated food and its features. Familiarity refers to the fact that consumers are acquainted with the labels used to identify irradiated food or not. Intent to purchase refers to whether consumers are willing to buy irradiated food or not. Each of the items was extracted from papers in the form of percentages or proportions.

Study risk of bias assessment

To minimize bias, the authors only included studies that provided explicit frequencies or relative frequencies on the concerned items or variables of interest. No conjecture was made with respect to a proportion or a percentage taken from a paper. Further, to validate results, each author was provided with a sample of included studies to generate the statistics for the research. The match between the authors was 100%, and, therefore, the method of coding was deemed reliable and valid. The searches conducted featured the presence of the keywords in the title of the paper. The Scopus search for all keywords generated 138 articles, while the search in the Web of Science database produced 129 articles. A large number of articles were duplicates (183) and were removed from the list of eligible studies. Many studies 46 were removed because they did not investigate acceptance or awareness despite the presence of such terms in their titles, making them irrelevant and thus removed. Finally, among the remaining articles, 11 did not provide statistics like frequencies on variables of interest and, therefore, were eliminated. The final number of included articles was 27.

Results and Discussion

Overview of the literature

Supplementary Table 1 presents the names of journals, their impact factors, and the number of papers published in each. There was a total of 21 journals publishing 27 papers on food irradiation acceptance, familiarity, and consumption intentions. One noticeable trend is the absence of impact factors among 10 journals. Radiation Physics and Chemistry appears to publish the greatest number of articles on food irradiation acceptance and Familiarity. Food Materials Research also seems to be a popular destination for papers on food irradiation perceptions. The remaining set of journals published a single paper on the topic, signaling the interdisciplinary nature of food irradiation perceptions literature.

The quality of papers addressing consumer acceptance, awareness, familiarity, and uncertainty concerning irradiated food suffers from several quality concerns. On the one hand, authors appeared to target journals with low to no impact factors, perceiving them as either easier venues for publication or faster journals for production. Another issue is the prevalence of convenient samples or student participants in consumer acceptance research on irradiated food. Top journal reviewers often reject papers relying on small, convenient samples, leaving authors with limited choices and seeking journals with no impact factor. Additionally, publication bias may play a role in creating the quality problem in consumer research on irradiated food. Journals tend to trust American or Western samples based on probability methods more than samples from the developing world, especially if such samples are based on non-probability methods. Figure 1 demonstrates the geo-

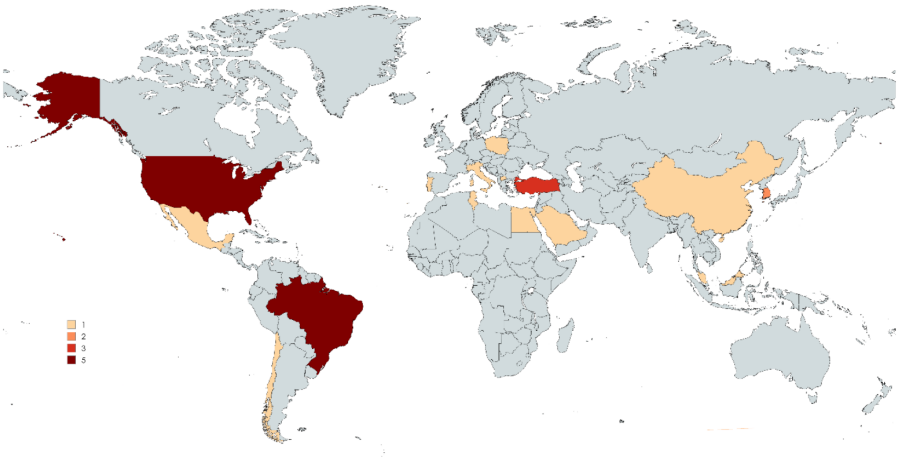

Figure 1. Geographic distribution of food irradiation studies.

graphic distribution of food irradiation acceptance, familiarity, and intention to purchase studies since inception. Despite the presence of the research area for more than four decades, the self-report perceptions literature is still limited to a handful of countries. North America seems to feature the largest number of studies originating from the US and Mexico. In Latin America, interest in irradiation is growing, as evident in the research from Brazil and Chile in the past decade. In Europe, the picture is more fragmented as Eastern European and Mediterranean countries lead the way with studies published with Turkish, Italian, Polish, and Macedonian samples. Western Europe seems to gloss over the perceptions concerning food irradiation in favor of other topics related to the subject, such as the feasibility of the technology and its potential impact on human life and the environment. Interestingly, two North African countries, Egypt and Tunisia, lead the way in the perceptions literature with two studies in the past decade. In Asia, Eastern states spearheaded the perceptions research compared to other countries on the continent, with China, South Korea, and Malaysia generating the investigations on acceptance, familiarity, and intentions among the public. Overall, studies on people's willingness to accept and consume irradiated food were found in 15 countries with a total sample of 24,474 people (Bord and O'Connor, 1989; Spaulding *et al.*, 2007; Byun *et al.*, 2009; Gallo *et al.*, 2022).

Table 1 demonstrates the sample sizes per country voicing their perceptions on food irradiation acceptance, familiarity with the labels, or intention to purchase such items. The study from the US appears to be the outlier in the literature, where its sample size equals 12,474. Ten countries' samples were lower than 700. Five countries featured samples of more than 1000 individuals. The majority of smaller samples reported the use of non-probability methods decreasing the quality of representation and adding further error to the estimation of their statistics (Kwon *et al.*, 1992; Prejean, 2001; Ibrahim *et al.*, 2022; Barkaoui *et al.*, 2023).

Table 2 presents descriptive statistics for the rates of acceptance, awareness, uncertainty about safety, intent not to purchase, and familiarity with labels concerning irradiated foods. Across all studies, the acceptance rate of irradiated food was 0.54 (mean), with an average variation of 0.19 (standard deviation). Across all existing samples reported in the literature, about half of the population accepted irradiated food to be ready for individual consumption in world markets. Further, the variability in acceptance of irradiated food seems to be high, with a 20% variation from one sample to the other. Note that this research reported the highest acceptance rate in each included paper, which could have been obtained after the delivery of new information or education sessions to participants.

Similarly, awareness of irradiated food exhibits an approximately identical pattern to the acceptance variable. On average, half of all participants across the samples reported being familiar with irradiated food. Several studies indicated low awareness levels concerning irradiated food (Galati *et al.*, 2019; Buczkowska *et al.*, 2023). One of the main reasons is the high skepticism regarding the safety of the food, evident in the high uncertainty rates reported elsewhere in the literature (Mehmetoglu *et al.*, 2007). About 26% variability rate exists across studies, signaling a high difference from one sample to another. Nevertheless, the reported awareness rates were also the highest reported in each included paper, which could have been obtained after being exposed to some type of information about them during the data collection phases across studies.

Concerning the uncertainty about irradiated food safety, half of all participants across samples indicated some type of concern. Additionally, the rate has varied considerably across research studies, featuring a standard deviation of 0.21. Across all studies, a quarter of the sample differed in their ratings of the concerns about irradiated food.

One of the most interesting results of this research is the low rate of individuals who intend not to buy irradiated food. Across all samples, about a third of participants indicated their unwillingness to purchase irradiated food. Such a result leads to the conclusion that more people are willing to buy or consume irradiated food compared to those who do not. The variability of the intent not to buy rate is smaller compared to other variables at 0.17 standard deviation. Therefore, on average, world populations appear to be

Table 1. Distribution of countries and sample sizes.

Country of the survey	Sample size
Brazil	1389
Chile	497
China	264
Egypt	500
Italy	392
Macedonia	92
Malaysia	276
Mexico	2107
Poland	609
Portugal	608
South Korea	1100
Tunisia	394
Turkey	2660
United States	12474

Table 2. Descriptive statistics for rates of acceptance, awareness, uncertainty about safety, intent not to purchase, and familiarity with labels.

	Rate of acceptance	Rate of awareness	Rate of uncertainty about safety	Rate of intent not to buy	Rate of familiarity with the labels
Mean	0.54	0.50	0.50	0.36	0.34
Median	0.6	0.49	0.52	0.39	0.47
SD	0.19	0.23	0.21	0.17	0.20
Range	0.68	0.85	0.7	0.61	0.49
Minimum	0.12	0.1	0.13	0.05	0.04
Maximum	0.8	0.95	0.83	0.67	0.53

SD, standard deviation.

similar in their willingness to buy irradiated food, especially after learning about their benefits and addressing the myths about their safety concerns (Loaharanu, 1995; Gunes and Tekin, 2006; Murray *et al*., 2024; Shubayr, 2024).

One of the consistent patterns across studies is the low familiarity with irradiated food labels. Familiarity with the labels of irradiated food is still low. On average, only 34% of all surveyed individuals reported being familiar with labels in those studies that reported such a statistic. Table 3 presents the bivariate correlations between rates of acceptance, awareness, uncertainty, and familiarity with labels concerning irradiated food. Most correlations are weak and of little practical significance, with few exceptions. First, the association between acceptance and uncertainty is moderate and negative, -0.36. Higher perceptions of uncertainty about the safety of irradiated food are associated with lower rates of acceptance. Similarly, higher rates of uncertainty were correlated with awareness, -0.25. It seems that low awareness levels are associated with more safety concerns. In addition, familiarity with the labels' perceptions was related to the intent not to buy irradiated food. Lower familiarity with labeling was associated negatively with higher intent not to purchase irradiated food (Resurreccion *et al*., 1995; Lima Filho *et al*., 2017; Hussin *et al*., 2018; Bolek, 2020).

Acceptance and familiarity

Figure 2 shows the distribution of acceptance and label familiarity rates over time concerning food irradiation. Note that the proportion of studies devoted to the investigation of acceptance was much larger than that on label familiarity. Generally, acceptance of irradiated food has increased over time. On the contrary, with few exceptions, familiarity with labels like Radura among consumers is still low.

The variability in acceptance and label familiarity rates' increase could be explained by the accessibility and availability of irradiated food in markets. For instance, the US appears to have more readily available irradiated food to consumers in grocery stores compared to other countries in the study (Behrens *et al*., 2015; Rusin *et al*., 2017). Thus, familiarity with labels increased at a much higher rate in the US compared to other developed and developing countries (Frenzen *et al*., 2001; Parrella *et al*., 2023).

Supplementary Figure 2 presents the distribution of studies in reference to their country of origin, as well as the samples' acceptance and familiarity with irradiated food. One may note the stark variability in acceptance and familiarity across samples. In the US, acceptance and familiarity with the tables seem to be higher compared to other countries. On the contrary, studies from Mexico, Brazil, and Chile reported low familiarity rates with irradiated food. The sampling and measurement characteristics appear to cause some of the stark variability in acceptance rates within the same country or across countries around the world.

Supplementary Figure 3 displays a scatter plot showing the relationship between rates of acceptance per study and sample sizes. Note the presence of a slight negative association between the two variables. As the sample size grows, the acceptance rate decreases slightly. Nevertheless, the slope is not steep, signaling a weak effect. One noteworthy observation is that most studies have sample sizes of less than 1000 individuals. Relatedly, most of these samples are non-probability-based representative samples, which could alter the observed statistics and their generalizability.

Figure 3 shows the association between familiarity with label rates and the sample size of studies. Despite the slight positive relationship, the slope seems to be close to zero, indicating a lack of practical association between the two variables. Sample size seems to have little effect on familiarity, supporting earlier evidence suggesting that familiarity is low across countries and over time.

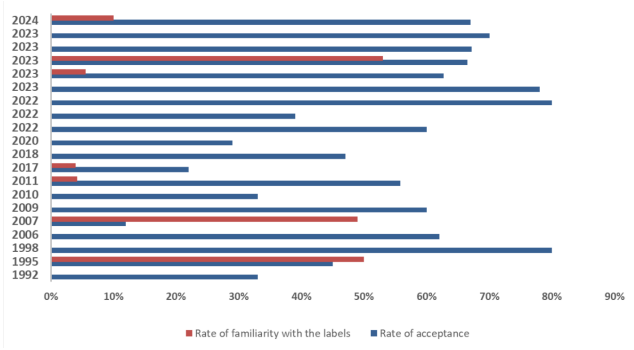

Figure 2. Distribution of acceptance and label familiarity over time.

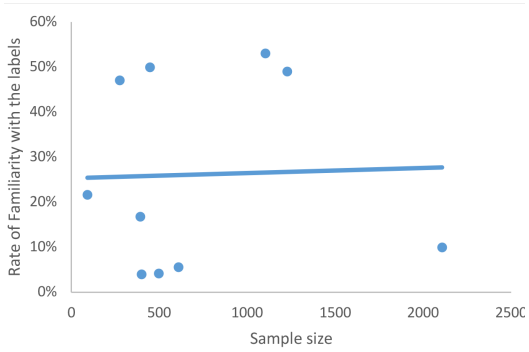

Figure 3. Relationship between familiarity with label rates and sample sizes.

Table 3. Correlations between rates of acceptance, awareness, uncertainty, and familiarity with labels.

	Rate of acceptance	Rate of awareness	Rate of uncertainty about safety	Rate of intent not to buy	Rate of familiarity with the labels
Rate of acceptance	1.00	0.03	-0.36	0.08	-0.19
Rate of awareness	0.03	1.00	-0.25	0.05	0.37
Rate of uncertainty about safety	-0.36	-0.25	1.00	-0.02	-0.03
Rate of intent not to buy	0.08	0.05	-0.02	1.00	-0.11
Rate of familiarity with the labels	-0.19	0.37	-0.03	-0.11	1.00

Consumers intentions

Supplementary Figure 4 presents the distribution of samples on their acceptance rates of irradiated food, as well as their willingness to purchase it. Notice that the included acceptance rate in the graph is the highest reported rate in each paper, which may have included more than a single acceptance rate. The reported rate represents the highest acceptance rate of people after presenting them with beneficial information concerning irradiated food in many papers. Therefore, the acceptance rates observed in the literature appear to be high. In each sample with both acceptance rate and intentions to purchase irradiated food, the percentage of individuals who reported acceptance exceeded those who did not under any circumstances.

Supplementary Figure 5 displays the relationship between intentions not to buy irradiated food and sample size across included papers. There seems to be a negative association between the two variables. As the sample size increases, the rate of intention not to buy irradiated food decreases. Alternatively, larger sample sizes that tend to be nationally representative snapshots of populations have rates of positive intentions to purchase irradiated food.

Supplementary Figure 6 presents an interesting association between acceptance rates and intentions not to buy irradiated food. It would be expected to observe higher acceptability rates to negatively correlate with the rates of intentions not to buy. Accepting irradiated food makes people more willing to purchase it. One potential explanation lies in the consumer mentality. While some may accept irradiated food to be sold in markets, they would not necessarily purchase it. For instance, alcohol functions in a similar way. One reason for not purchasing irradiated food while accepting its consumption is the availability of cheaper alternatives. Irradiated food is more expensive compared to other choices on the shelf. Consumers may have the same acceptance rates for both or otherwise, yet choose to purchase non-irradiated food to save money on groceries.

With a growing demand for food supply and safety across the globe, food irradiation emerges as a viable strategy for fulfilling increasing pressures (Galati *et al*., 2019). The number of e-beams facilities is rising, especially in nuclear countries like China, which provides the world with about half of the existing supplies of irradiated food today (Wang *et al*., 2023). This research paints a positive correlation between the increasing consumer acceptance of irradiated food as a normal choice for ordinary consumption and the investment in technology enhancement from governments around the world over time. It is evident that acceptance and awareness increased in the past three decades, with a parallel increase in the number of facilities, investments, and expansions of irradiated food facilities. This trend is probably going to grow over the next decade.

One of the most noticeable trends in the research on irradiated food is the geographic expansion of the literature to new countries beyond nuclear nation-states. While the US dominated the literature at the beginning, the spread of consumer acceptance studies carved new territories like South America, Eastern Europe, North Africa, and East Asia. More recently, interest in irradiated food acceptance or awareness has reached new markets like Turkey, Poland, Egypt, and Macedonia. The literature is expected to grow, reflecting the new investment in irradiation facilities around the world. Food irradiation is no longer a developed nations' issue; it is a global affair engaging the developing world as well.

An important finding in this research, confirming earlier results on consumer acceptance of irradiated food, is the impact of information on people's perceptions. On the surface, this study corroborates earlier findings suggesting low familiarity or awareness rates among consumers of irradiated food or their labels. By the same token, this research demonstrated that acceptance increases after exposing participants to positive information on irradiated food. Similarly, participants' safety concerns diminish once they learn about the safety of the technology. This research highlights the need for further investment in mass education campaigns to the public concerning irradiated food safe consumption.

Contributions

On theoretical grounds, this research shows a weak positive correlation between irradiated food acceptance and intent not to buy such items. This evidence directly contradicts the theory of planned behavior's assumption that positive attitudes toward irradiated food will lead to higher levels of intention to consume such foods. D'Souza *et al.* (2021) argued that the theory of planned behavior explained 35% of the variance in consumers' intent to purchase irradiated food. Relatedly, the authors extended the original model by adding trust and risk, increasing the percentage to more than 50%. Such findings were particular to a single sample. In this research, a revision to the logic of planned behavior utility in providing sufficient explanations is invoked. This is especially true when many people accepted irradiated food as positive and yet expressed unwillingness to purchase it.

Arising from the foregoing theoretical discussion, this study calls for further theoretical study incorporating other models in parallel with the theory of planned behavior to explain irradiated food consumption. This research reported that uncertainty about food safety is a primary factor in people's consideration of consuming such food. By the same token, familiarity with such food in many markets is still low. Therefore, health benefit models or information, motivation behavioral models could present opportunities to improve the understanding of why individuals decide to consume irradiated food. Given the technology element of food irradiation, many would argue that the technology acceptance model logic may also apply to this context. If people perceive irradiated food as useful and easy to produce, market, refrigerate, and consume, they may be more willing to purchase it. In this research, an appeal is made to future researchers to build unified models incorporating more than a single theory to reach more accurate results. Model utilities are governed by their usefulness rather than domain reach or popularity in the behavioral literature.

One potential explanation for the contradiction between the present study and prior research concerning the relationship between acceptance and intention to purchase irradiated food is price. On the one hand, samples in previous studies showed relatively high acceptance rates of irradiated food. On the other hand, despite such acceptance, the same samples indicated high intentions not to purchase irradiated food. The price tags on irradiated food labels discourage consumers from purchasing such food, even if it is accepted. Such an association is moderated by income. The present study features samples from developing countries, which possess lower purchasing power compared to developed economies. Thus, the relationship could be explained by price.

One of the noticeable findings in this research is the high acceptance rate of consumers toward irradiated food after learning about its useful properties and easy production processes. Such evidence lends support to the technology acceptance model (Davis *et al*., 1989). While few researchers have explicitly tested the technology acceptance model in its original form (Davis *et al*., 1993) or newer versions (Venkatesh and Bala, 2008), the theory appears to be relevant, especially when one considers uncertainty about

irradiated food safety. Many consumers believe that irradiation as a technology poses safety concerns, and therefore are unwilling to purchase irradiated food. Such evidence is clear in a study by D'Souza *et al*. (2021), which added trust, increasing the explanatory power of their model. Thus, trust in the technology led to the improvement of consumers' acceptance of the technology.

Future research directions

One of the future research areas of interest with respect to consumers' behavior in the realm of irradiated food is the investigation of the causes leading many people to accept such food, and yet still intend not to purchase it. According to behavioral models like the theory of planned behavior, if people possess positive attitudes about a specific behavior, they are more likely to express high levels of intentions to engage in such an act (Ajzen, 1991; Buczkowska *et al*., 2023). In this research, the findings suggested that a considerable number of people accept irradiated food and consider it safe. However, they still intend not to buy it. Such a dynamic is interesting and worthy of future investigation. One way researchers may approach this area is through the use of mediation analysis, exploring the power of specific perceptual constructs such as trust, risk tolerance, or openness to new experiences (Ajzen, 1991; Bruhn, 1998; Nayga *et al*., 2005; Behrens *et al*., 2009). The present study uncovered widespread variability with respect to irradiated food acceptance, awareness, and purchasing intent. While most researchers may resort to the classic argument of methodological specifications causing the changes observed across studies, this research highlighted differences based on geography and culture. For instance, the US and South Korea samples appeared to be more approving compared to the Turkish, Polish, and Macedonian ones. Studies also reported that urban residents and those with higher levels of education tend to be more accepting and aware of irradiated food. Does modernization explain a proportion of such variance among populations? To what extent does variability in consumer types or categories affect food irradiation acceptance or consumption? Future researchers are urged to explore explanations and collect data on such explanatory variables to better understand why some types of consumers perceive irradiated food differently from others.

Limitations

As with any review, the current paper suffers from numerous design and subjective biases. Notably, the rates used in this investigation, acceptance, awareness, and familiarity with labels rates were the highest indicated statistics within each paper. For instance, if a paper reported five different acceptance rates for irradiated food consumption, the highest number was taken. Therefore, this paper appears to reflect high acceptance and awareness rates. For most papers reviewed, high acceptance and awareness rates were reported after being exposed to an educational program or positive information about irradiated food. In many cases, acceptance and familiarity were very low prior to receiving any form of education or information. Therefore, interpreting the results in this research must keep in mind that the numbers reported were the highest in their realm.

Another limitation beyond the control of the researchers is the presence of all rates in each of the reviewed papers. Unfortunately, many papers reported a few, but not all, of the concerned rates with respect to irradiated food consumption. For instance, many studies did not indicate the rates of label familiarity. Relatedly, in many instances, authors have not provided complete information concerning the rates calculated. In such cases, the researchers took the available information and performed different calculations to reach the final reported rates. The variability in methods of estimation depended on the type of information provided by the original researchers. Thus, levels of subjectivity have impacted the reported statistics used in this research.

Conclusions

This study provides a comprehensive synthesis of global perceptions regarding irradiated food, revealing an overall increase in acceptance and awareness during the past three decades. Despite widespread misconceptions, particularly concerning safety and radioactivity, the study highlights the crucial role of information and education in transforming consumer attitudes. Acceptance of irradiated food has risen significantly, although familiarity with irradiation labels remains low. Geographic and cultural factors contribute to variability in acceptance rates, with developed countries generally showing higher acceptance. Developed economies featured higher awareness and acceptance rates toward irradiated food compared with developing economies. Such an observation is partly explained by higher levels of technological advancement and educational rigor, as well as the quality endowed in advanced economies like the US and South Korea. The findings underscore the need for targeted educational campaigns to address misconceptions and enhance consumer confidence in irradiated food, providing valuable insights for policymakers and stakeholders aiming to promote food irradiation as a safe and viable technology. Trust in science could explain the variation in accepting and consuming irradiated food. In Western countries, where science is trusted, people are more willing to purchase irradiated food because they tend to believe in the benefits of the products based on experimental evidence. In countries where science is not trusted and religion is strong, people tend to suspect technological advancements in favor of traditional products. In this research, Middle Eastern and North African countries tended to suspect the viability of irradiated food more than the US, South Korea, or Brazil.

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Online supplementary material:
Supplementary Table 1. Names of journals, their impact factors, and the number of papers published in each.
Supplementary Figure 1. Search process and results.
Supplementary Figure 2. Distribution of acceptance and label familiarity by country.
Supplementary Figure 3. Relationship between acceptance rates and sample sizes.
Supplementary Figure 4. Distribution of acceptance rates and willingness to purchase.
Supplementary Figure 5. Relationship between intentions not to buy and sample size.
Supplementary Figure 6. Relationship between intentions not to buy and acceptance.