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Consumer Perception and Acceptance of Nanomaterials in the Food Industry: A Comparative Analysis with Risk Potential

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Nadi Bulathsinghalage-Cooray BSc

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Abstract

Diese Arbeit untersucht die Wahrnehmung und Akzeptanz von Nanomaterialien in der Lebensmittelindustrie durch Konsumenten, insbesondere die Auswirkungen des wahrgenommenen Risikos auf die Einstellung und Akzeptanz der Verbraucher. Die Studie befasst sich mit der Notwendigkeit, die Wahrnehmung der Verbraucher in Bezug auf neu entstehende Lebensmitteltechnologien, insbesondere Nanotechnologie in Lebensmitteln, zu verstehen. Viele Lebensmittelindustrien setzen heutzutage Nanotechnologie ein, um die Qualität, Sicherheit und Haltbarkeit ihrer Lebensmittelprodukte und ihrer Verpackungen zu verbessern. Die Einstellung der Verbraucher zu Nanomaterialien hängt von vielen Aspekten ab. Dazu gehören die gesundheitlichen Auswirkungen von Nanomaterialien, die Auswirkungen auf die Umwelt, das Vertrauen in die Aufsichtsbehörden und die Wirksamkeit der Risikokommunikation. In dieser Arbeit wurde eine systematische Literaturrecherche anhand von begutachteten Artikeln aus den Datenbanken Scopus, ScienceDirect usw. sowie eine zusätzliche manuelle Suche durchgeführt. Die Ergebnisse zeigen, dass das Vertrauen der Öffentlichkeit in die Regulierungsbehörden, der wahrgenommene Nutzen und die Risiken sowie die Transparenz der Risikokommunikation die Verbraucherakzeptanz erheblich beeinflussen. Die Verbraucher erkennen zwar die potenziellen Vorteile von Nanomaterialien und -produkten an, äußern sich aber auch skeptisch, da die langfristigen Auswirkungen auf die menschliche Gesundheit und die Umwelt ungewiss sind. Die Studie legt nahe, dass transparente rechtliche Rahmenbedingungen, wirksame Risikokommunikation und Aufklärung, die Akzeptanz der Verbraucher deutlich erhöhen können. Wenn sichergestellt wird, dass Sicherheitsbewertungen, Überwachungsbehörden und Aufklärungsprogramme standardisiert sind, können die Ängste der Verbraucher verringert werden. Diese Arbeit bietet eine systematische Auswertung der Literatur, um zu zeigen, wie sich die Risikowahrnehmung auf die Verbraucherakzeptanz der Nanotechnologie in der Lebensmittelindustrie auswirkt.

Abstract

This thesis investigates consumers' perception and acceptance of nanomaterials in the food industry, and more specifically, the effect of perceived risk on influencing consumers' attitudes and acceptance. The study deals with the necessity of understanding consumer perceptions of emerging food technologies, primarily nanotechnology in food products. Many food industries nowadays are using nanotechnology to enhance the quality, safety and shelf-life of their food products and even their packaging. Consumer attitudes towards nanomaterials depend on many aspects. They include the nanomaterials' health effects, environmental effects, confidence in regulatory bodies, and effectiveness of risk communications. The thesis conducts a systematic literature review through peer-reviewed articles from Scopus, ScienceDirect databases, etc., plus an additional manual search was conducted. The findings indicate that the public's trust in regulating authority, perceived benefits and risks and the transparency of risk communication significantly affect consumer acceptance. Consumers may recognise the potential benefits of nanomaterials and products; however, they also express scepticism due to the uncertainty regarding their long-term effects on human health and the environment. The study suggests that transparent regulatory frameworks, effective risk communication and education can significantly increase consumer acceptance. Making sure that safety assessments, monitoring authority and consumer education programs are standardised improves consumer fears. This thesis provides a systematic assessment of the literature to shed light on how risk perception affects consumer acceptance of nanotechnology in the food industry.

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1. Introduction to the Role of Nanomaterials in Food Industries and Consumer Perception

In recent years, nanomaterials have gained prominence across diverse industries, with applications ranging from cosmetics to the food industry. The food sector perpetually seeks novel materials and technologies to augment product quality and meet the evolving demands of consumers. Nanotechnology is gaining prominence in the food and agriculture sector, with several key applications helping improve the quality, safety, and production of food products. Not only do nanomaterials impact the food, but they also impact the customer. Many food packaging products, dietary supplements, and some food ingredients available on the market contain engineered nanomaterials. As a result, the successful incorporation of nanomaterials into food products relies significantly on consumer perception, acceptance and recognised risks (Brown and Kuzma, 2013; Yue *et al.*, 2015). Without these factors taken into consideration, the food industry will face hardships trying to convince consumers of nanomaterials in their food products.

Nanotechnology offers considerable potential to the food industry as well as risks and it is essential to understand how consumers perceive these risks and whether they can accept such risks. Nanomaterials that help in food packaging and production can offer food safety, shelf-life enhancement, and nutritional properties enhancement. However, experts are not sure about the safety of nanomaterials because some studies show that they may harm human health and the environment. Research shows that consumers are aware of the benefits of nanotechnology in food. But most of them seem suspicious, with many stating that they could be risky (Murphy *et al.*, 2022). These risks have recently surfaced and health institutions like the FDA in the USA and EFSA in Europe must tackle these challenges.

Recent research highlights that consumer acceptance of nanotechnology is influenced by their perceptions of the balance between benefits and risks. As well as their trust in authorities, and clear risk communication, all contribute to levels of acceptance. People's opinions on nanomaterials are influenced by social and environmental factors. A recent study of consumer reaction to food products modified using nanotechnology shows that consumers are more likely to accept nanomaterials when they trust that regulatory authorities are monitoring food safety. It is important that the risks as well as benefits are communicated (Siegrist and Hartmann, 2020). People are more likely to say yes to nanotechnology in food products when they see personal benefits (e.g. better health or lower cost) but become sceptical if safety issues are raised (Zhao, Yue and Kuzma, 2020). Government authorities on food and public health must play an important role in the newest innovations in food tech.

Governance of ‘nanotechnology’ is also a big issue. The regulatory frameworks of nanomaterials are still being developed. Although they are becoming popular for uses like food packaging and nutrient delivery systems, major gaps remain in risk assessment. The European Food Safety Authority (EFSA) believes that standardised in vitro and in vivo tests are essential in ensuring consumer safety, particularly in consideration of potential nanotoxicity (Xavier *et al.*, 2021). To accomplish all their goals and to operate accordingly, funding must be ensured. In general, the public views these agencies as competent and trusts them to handle said innovations in the industry.

However, doubts about the current regulations are creating scepticism on the migration of nanoparticles from packaging into food (Tarhan, 2020). Still, recent works of nanotechnology show a lot of potential for improving food safety and quality. For instance, some studies have shown that nanomaterials in packaging can effectively reduce microbial contamination and improve the shelf-life of the product without posing a significant threat when managed suitably (Mustafa and Andreescu, 2020).

1.1 Aim of the thesis

Negative consumer attitudes about nanotechnology in food come from health concerns and a lack of confidence in regulatory risk management for these new types of technologies. It appears that while many prospective consumers would welcome the application of nanomaterials in foods, the deep-seated reluctance persists mainly due to scepticism concerning the long-term health outcome of nanotechnology, as well as the great silence on risk communication by industry stakeholders (Mustafa and Andreescu, 2020). A clear and transparent regulatory framework that is complemented by uncomplicated risk communication strategies may assist in resolving these questions and boosting customer acceptability of nanomaterials in the food sector (Ahmed *et al.*, 2021). These factors will be important towards the responsible development of nanotechnology and enabling its benefits to be leveraged in a way that does not evoke any backlash.

This thesis aims to analyse how consumers' attitudes towards nanomaterials in food are determined by the concerns of health risks, environmental issues, and the trust level of regulatory authorities. Research shows that individual characteristics such as food neophobia, trust in the food industry, and the expected usefulness of nanotechnology often determine the level of consumer acceptance of nanomaterials in food (Siegrist and Hartmann, 2020). In addition, the level of consumer pressure to ensure the safety of such technologies is affected by how the regulators of nanomaterials are seen to provide that oversight (Murphy *et al.*, 2022). This paper seeks to evaluate not only the risk perception but also the risk acceptance metrics of consumers to new nanotechnology information. There is evidence that explains the way consumers can be willing to accept nanomaterials in foods so long as they are properly educated on the unique advantages, such as positive changes, that will be brought to food and its packaging (Zhao, Yue and Kuzma, 2020). Still, there are lingering issues with the perceived safety and health risks that may abound with the overuse of such technologies that must be addressed adequately to gain consumer trust in the products (Xavier *et al.*, 2021). If these consumer concerns are not addressed, confidence will perish in novel food products and innovation will be hampered.

1.2 Scope and Relevance

Relevance Nanotechnology is more and more considered as a technology that can satisfy the existing problems with food quality, safety and nourishment. According to various applications, technology offers potential solutions for these problems concerning shelf-life extension, food quality enhancement, and food safety assurances. Nevertheless, even with these improvements, there are still challenges regarding safety and health regarding the use of nanomaterials in food products. Research such as that of Venkatakrishnan et al. (2024) argues that nanotechnology can be beneficial in safety against food contamination (Kiran *et al.*, 2024). At the same time, as one of the most popular tasks of researchers is the synthesis of nanomaterials that increase the bioavailability of products and the shelf life of foods, they also express the need for more studies to be done regarding these health risks (Ansari, 2023). As explained before, without high trust in the food product and the producer, consumers will stick with conventional foods.

Nanomaterials have assumed a critical position in food and agricultural packaging as well as preservation systems due to their added barrier properties, antimicrobial effects, and greater strength. For example, silver nanoparticles and titania are incorporated into packaging systems to inhibit contamination and increase the shelf-life of food materials (Chaudhary, Fatima and Kumar, 2020). Food and even food packaging have utilised nanotechnology in ways that not only limit its application to prolonging the freshness of the food, such as antibiotic coating, but also the early detection of bacteria in foods and the assurance against the cause of dreadful conditions. This is extremely important in solving such problems as food waste and destruction, wherein nanotechnology becomes an essential strategy for unyielding food security (Ahmed *et al.*, 2021). Food sensors and different detection methods also increase health security by warning of dangerous pathogens or bacteria in said product.

Apart from playing a significant role in packaging, nanotechnology is also used in food processing to modify the taste, texture and nutritional value of food. Enhancement of nutritional value and taste of food products is achieved through such actions as the use of nano-encapsulated nutrients that will allow for targeted nutrient delivery. It is particularly critical for those suffering from undernutrition, especially for those populations in developing nations where undernutrition remains a serious issue (Ranjha *et al.*, 2022). The improvement of nutrient absorption with the help of nanotechnology could solve many health problems caused by poor diets

Still, the frequent invention and vast utilisation of nanomaterials in the food industry pose safety threats. Some studies have found that certain nanoparticles, including but not limited to titanium dioxide, zinc oxide, and silver nanoparticles, can breach biological barriers and hibernate in human tissues, which may increase the probability of affecting organs or even resulting in cancer (Lu *et al.*, 2021). Such health risk factors highlight that further risk assessment studies and policy actions are essential to ensure that the nano foods are safe (Xavier *et al.*, 2021). Besides, the issue of possible chronic exposure to nanomaterials because of their regular consumption regularly raises the issue that more studies on the toxicological effects of nanomaterials are warranted.

Despite the increasing use of nanomaterials in the food sector, their legal framework is still under construction in the food industry. There is a lack of clear procedures and uniform methods to assess the safety and environmental status of these substances. Authorities in Europe have become aware of the fact that nanomaterials require a legal framework for use in food. The EFSA is going to undertake activities on the definition of assessment frameworks for nanomaterials. They stress that the important thing is to have a systematic approach to analysing the development of tools and technologies for the evaluation of possible hazards. Relevant guidelines are necessary to prevent the maladaptive development of food nanotechnology (Tarhan, 2020). Such developments can disturb consumer safety and environmental health.

1.3 Problem Statement

The utilisation of nanotechnology in food production, food processing and food packaging is considered a revolutionary development that can improve the freshness of food, enhance food safety, and help in better nutrition delivery. While there may be some positive impacts from the use of nanotechnology in the food sector, there are equally hefty negative effects on human health and consumer perception. It is essential to understand the acceptability of the application of nanotechnology to consumers, keeping in view safety and risk, to ensure the successful commercialisation of such innovations. The public's lagging confidence in a technology improvement process can cause great harm in the food industry, where consumer factors dictate market consumption (Zhao, Yue and Kuzma, 2020). In this context, it is essential to examine the effect of consumers' assessment of the potential risks and benefits of nanomaterials in food products on their purchase behaviour and receptivity to these nanofood products.

The more informed consumers are about the advantages and disadvantages of nanotechnology, the more likely they are to accept it in food. Studies have found that consumer willingness to adopt food products is possible with the right type of effective communication. Especially the positive aspects of nanofood, such as enhanced safety, quality and security of food, must be pronounced. Many people are enthusiastic supporters of most of the recent technological inventions, which come along with lots of benefits, but when it comes to the use of nanoparticles within the body, there are some negative perceptions. According to Zhao et al. (2020), consumers' acceptance of nanotechnology is based on the information recipients receive. Consumers are willing to pay more for nano-packaged foods if they are informed about the benefits and safety of the products (Zhao, Yue and Kuzma, 2020). Nanotechnology must be appropriately communicated, openly to the consumers, who have been trained to become quite more reluctant to buy the most recent products due to the adverse effects of confidence on health and nanoparticles inside the products.

Consumer attitudes towards food nanotechnology rely on the concept of risk. According to Mukherjee et al. (2019), nanotechnology can transform the food and agriculture industry. However, the barrier to its entry is always going to be the fear of health risks due to the use of nanoparticles. Most importantly, they found that the possibility of nanoparticles entering the blood and moving across biological barriers, such as the intestinal walls, poses health risks to human beings. The doubts from the past are made worse by the lack of toxicological information and regulatory standards that guide what is safe or 'acceptable' levels of nanomaterials in food (Mukherjee *et al.*, 2019). Due to a lack of information, consumers are not sure how ingesting nano-engineered products over a long period of time will affect them and therefore can try to avoid novel foods.

Consumers' view of safety is affected by their lack of knowledge regarding legal regulations in food nanotech. Fears of using nanomaterials in food have been developing among consumers. In reaction to concerns like this, regulatory bodies like the FDA in the U.S. and EFSA in Europe have been creating guidelines for using nanomaterials in food. These guidelines concern the packaging of the product and how the food is made. Considering these developments are ongoing, there still exists an abundance of uncertainty about the issues on safety issues concerning nanoparticles. In a study conducted in Spain, consumers were more open to nano-enabled packaging when they trusted that the regulators would effectively control the use of nanotechnology for food products. However, when it came to nano-enhanced products that might have at least some contacts with food items, even at low risk, they were not keen on purchasing them. An example would be the application of nanomaterials in packaging. The consumers' fears of nanoparticles leaching into food made them shy away from such products (Pérez-Esteve *et al.*, 2022). This supports the idea that consumers feel assured when adequate information about nanotechnology products and their stringent regulatory policies reaches them.

In addition, the perceived effect of nanotechnology on the environment is an important element that shapes consumers' viewpoints. More and more people understand that food production and packaging technologies affect the environment, and nanotechnology is being sought to be regulated accordingly. As was indicated by Ahmad et al. (2023), although nanotechnology is promising for food packaging's biodegradability and minimally generates packaging waste as a solution, consumers are still worried about the life cycle of nanomaterials and their ecological consequences for the environment. Some of those concerns are environmental effects, which are associated with safety, where consumers do not only worry about the health effects of nanoparticles, but fear that there is a possibility of harm to the environment, which extends to the ecosystem, unless nanoparticles are properly regulated (Ahmed *et al.*, 2021). The lack of such long-term studies about the ecological effects caused by these nanomaterials only serves to intensify this fear, making it important for health-related studies in the future to incorporate ecological health risks as well.

To analyse how consumers view the risks and benefits of nanotechnology, it is also necessary to determine their level of neophobia - the level of resistance to new technologies. Pérez-Esteve et al. (2022) note that prestige and higher technological neophobia were associated with refusing to accept nano-enhanced food packages even after persuasion about their safety and other relative advantages. This shows the psychological hurdles that need to be crossed to broaden the consumer acceptance base. Programs to educate the public to help alleviate the fear of the unknown concerning nanotechnology are likely to be most important in changing consumer perceptions (Pérez-Esteve *et al.*, 2022). Food producers and policymakers could collaborate to help address these hurdles and try to create a more well-informed and open-minded population towards nanotechnology by making it less confusing and more consumer friendly.

There are many benefits of nanotechnology regarding food extension, safety and nutrient delivery, nevertheless, the question still lingers about whether it will be successful in the food sector. One question is largely based on consumer perception regarding the safety and efficacy of nanotechnology. Consumer confidence in nano-food needs to be gained and acceptance of it needs to be earned by properly addressing their concerns regarding health consequences, technology's oversight, growth, and ecological outcomes (Zhao, Yue and Kuzma, 2020), (Pérez-Esteve *et al.*, 2022). More information on the chronic toxicity of nanomaterials, along with dialogue and good legislation, will be critical in addressing these issues and unlocking the full potential of food systems nanotechnology.

1.4 Methodology: Systematic Literature Review

In this research, a systematic literature review (SLR) approach is utilised to fill the gap in the studies on consumer perceptions as well as on the risk potential of nanomaterials in food products. The review process from Snyder (2019) was the preferred SLR approach to facilitate a thorough and consistent review of all published works regarding peer-reviewed literature to be able to derive valid conclusions from such literature. The assessment aims at ascertaining the main themes that have been researched and the existing disconnects in the studies, as well as how consumer perceptions agree or disagree with risk assessments and management.

1.4.1 Search Strategy

Electronic academic resources Scopus, Science Direct, usearch univie, PubMed, MDPI, Research Gate and Google Scholar were used for this SLR. The search employed several key terms such as "food," "nano-food," "nanomaterials," "nanotechnology," "nano-packaging," "consumer acceptance," "public opinion," "consumer perceptions," "risk management," "risk-assessment," and "safety concern". Boolean terms (AND, OR) were used to get more specific results. The search queries applied were as follows:

1) ("nanomaterials" OR "nano-food" OR "nanotechnology" OR "nano-packaging") AND ("consumer perception" OR "consumer acceptance" OR "public opinion") AND ("risk assessment" OR "risk management" OR "safety concerns")

2) ("Food") AND ("nanomaterials" OR "nano-food" OR "nanotechnology" OR "nano-packaging") AND ("consumer perception" OR "consumer acceptance" OR "public opinion") AND ("risk assessment" OR "risk management" OR "safety concerns")

A further literature search is implied, where reference lists of pertinent articles were scanned for any articles that were missed in the primary search. Keywords had to be found in the article, abstract, or the keyword section of the paper itself. Only then was a paper accepted to be recorded in the PRISMA Flow Graph. The different electronic sites provided the following number of papers after applying the search queries mentioned above: Scopus 28, Science Direct 40, PubMed 3, and usearch univie 19. Through a manual search on sites like MDPI and Google Scholar, 89 articles were acquired. This manual search had to be conducted to acquire articles that discuss topics outside of nanotechnology. The terms “Genetic Modification” or “GMO” and “Food Irradiation” are used to compare their life cycle as novel food innovations with the implementation of nano-enhanced foods. With the 90 results from before, 179 articles are collected in total. After further investigations, the total number of papers used in this thesis is 109.

PRISMA Flow Diagram

Identification

Records identified through database searches (n = 90)

Additional records identified through manual search (n = 89)

Total records (n = 179)

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Duplicate Removal

Records after duplicates removed (n = 165)

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Screening

Records screened via titles/abstracts (n = 165)

Records excluded (n = 57)

Records for full-text review (n = 108)

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Eligibility

Full-text articles assessed (n = 108)

Full-text articles excluded, with reasons (n = 0)

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▼

Included

Studies included in qualitative synthesis (n = 108)

1.4.2 Inclusion Parameter

To incorporate the most pertinent and high-quality studies available into this structured literature review, the specific set of inclusion and exclusion criteria is adhered to very strictly. The inclusion criteria placed particular emphasis on the identification of peer-reviewed articles that had been published in reputable journals to ensure that the research has an admirable academic standing. More specifically, studies centred on the application of nanotechnology in the food industry and whether they addressed consumer perceptions, risk communication or safety assessments. These criteria are necessary to ensure that the selected articles are relevant in meeting the objectives of the thesis. In the manual search, a few papers delving into GMOs and Food Irradiation are accepted in this work, mainly to highlight similarities and consumer acceptance levels. These technologies brought about a new era for the food industry, so their insights are important to compare with. To obtain current developments and dynamic trends in this fast-moving field, the thesis contains literature that was published within the last 11 years, from 2013 to 2024. This time frame was chosen to ensure that the research addresses the most recent issues in the use of nanotechnologies in the food industry. In addition, all articles are in English to promote uniformity and comparability of the studies and ease of access for the readers of this thesis.

1.4.3 Exclusion Parameter

Conversely, exclusion criteria aimed at removing studies that stray too far from the focus of the review were used as the opposite parameter. Not true research papers, for instance, those that do not relate to food and nanotechnology usage, are removed along with opinion pieces, editorial opinions, and organisational reports. Additionally, besides preprints, studies that dealt with non-subjective aspects of nanotechnology, excluding those that relate to food, are disregarded. Such a position is taken in order not to extend the research over the scope of consumer attitudes toward nanotechnology used in food products and their associated risks. Redundant literature and literature that provides scant detail regarding the methodology employed in the selection or reporting of studies are removed to preserve the integrity and quality of the review. These criteria ensure that the studies that are included are not only relevant to the thesis at hand but also maintain a sound scientific logic, making it a strong base for the thesis.

1.4.4 Quality Assessment

Standard operating procedures are established to ascertain that every single article possesses the requisite quality to be considered for the review. Quality assessment concentrated on the design of the studies, a canonicality review concerning the posed research problems or the efficacy of the analysis performed on the data gathered. Studies from 2013 to 2024 are favoured as they show the utilisation of good experimental designs or systematic reviews, since those methods yield better and reproducible results. Studies that have a methodological framework are stressed upon as they mean that the findings are supported by appropriate research logic. The distribution of papers by methodology that are chosen at the end can be seen in the Chart below:

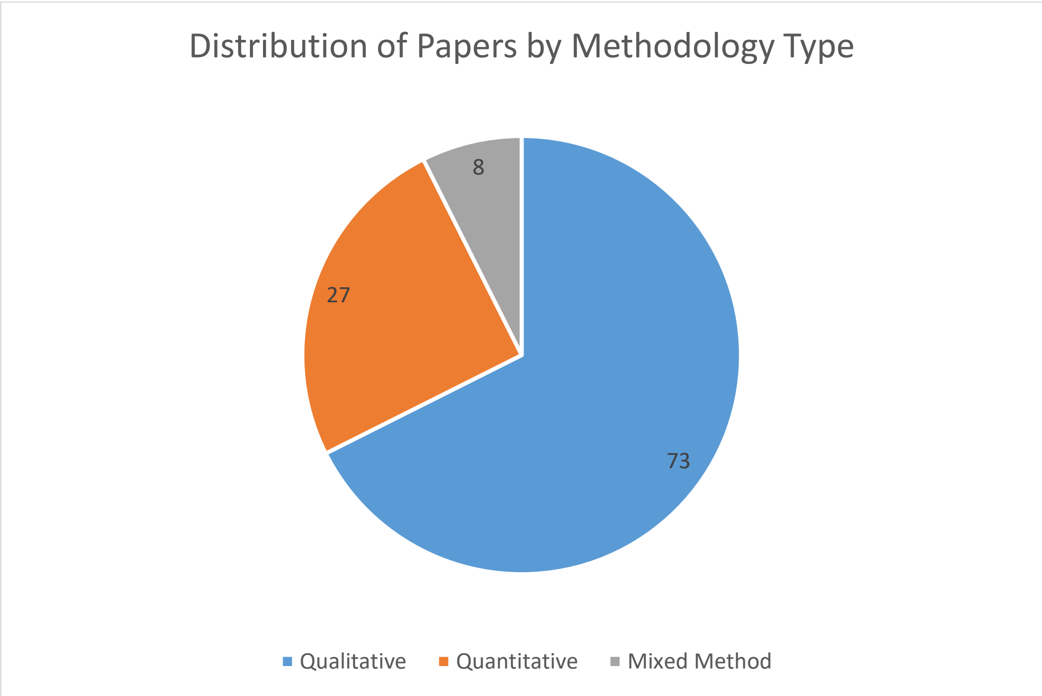

Figure 1: Distribution of Papers by Methodology Type

Figure 1 shows how many studies use one methodology or another according to this systematic literature review. The majority, 67.6%, of the studies in the review use qualitative methods like literature reviews, expert interviews, or thematic analyses. A lot of literature is exploratory, i.e. it focuses on theories, regulations, and consumers rather than testing the real products.
Conversely, 25.0% of the studies use quantitative methods such as surveys, statistical modelling, experimental designs, and risk assessments. These analyses offer quantifiable information regarding consumer acceptance, toxicological effects, and market viability of implementing nanomaterials in food products. A smaller number of studies were reviewed, 7.4% of them employed mixed methods, meaning both qualitative and quantitative. The reviewed studies that rely on quantitative techniques mostly consist of surveys, experimental tests, and statistical modelling.

The dominance of qualitative studies implies a primary focus on a conceptual approach and regulatory discussions. Meanwhile, the small number of quantitative and mixed studies highlights a lack of evidence. Going forth, much focus must be given to conducting more quantitative analyses and experimental studies to enhance the evidence base supporting the benefits and risks of nanomaterials in food applications.

Relevance is defined as the most important in terms of quality assessment. This study focuses only on those that are pertinent to consumer perceptions, risk communication, and risk assessments of nanomaterials present in food. This is done to ensure that the studies that are included in the review correspond with the objectives of the thesis and add value to the research questions. Some exceptions are made to allow for comparison between food revolutions like GMOs and Irradiation. In addition, the level of analysis is very tight, and studies are evaluated on the methods used in the respective studies and the reproducibility of their results. The validity of measures employed to analyse data from each of the studies is assessed, and notions originating from them are applied in such a way that they would be relevant within the context of the intended research. Meeting these standards lets the review include works which are not only of high academic quality but also shed light on consumers' perception of the risk associated with nanotechnology in foods in a constructive way.

A structural review approach is adopted to synthesise the results of the articles. This makes it possible to review the literature in such a way that common themes, inconsistencies, and areas that need further exploration can be highlighted. The structural review is useful in establishing the gaps between the consumer views of nanotechnology in food and the actual risk assessment, as well as the need for communication in such perceptions. This approach makes it possible to ensure that all the pertinent issues that have been studied on consumer awareness and attitudes towards nanotechnology in the food sector are canvassed in the first part in preparation for the analysis and discussions later in the thesis.

1.5 Research Question and Objectives

This thesis aims to study the consumers' attitudes and acceptance of the usage of nanomaterials in the food industry with due regard to probable risks. Nanotechnology is recognised as one of the techniques that are transforming the food industry, as food safety, preservation, and other nutritional delivery have improved. In this section, the research question will be investigated and its three sub-questions. These questions are aimed at understanding important consumer perceptions and acceptance of nanomaterials in food.

According to the authors Mukherrjee et al. (2019) and Pérez-Esteve et al. (2022), the current works do not do much to take care of the safety and environmental effects of using nanomaterials in food for long durations. The authors Mukherjee et al. are positive about the nanotechnology power improve food production. However, according to them, not many metabolic and other elaborate studies are available that could affirm the safety of the materials from a health risk point of view. This highlights the importance of more studies in the field (Mukherjee *et al.*, 2019). Pérez-Esteve et al. also caution that nanotechnology can improve the safety and packaging of food to an incredible extent. However, the information about the materials used in the package and their interactions in the food system without any knowledge of time is inadequate and leads to poor health (Pérez-Esteve *et al.*, 2022). So, detailed studies need to be conducted to know the risk of the materials in old foods. Further research is essential to close the gaps in knowledge and safety which stand in the way of the acceptance and regulation of nano-foods.

i. HOW DO CONSUMERS PERCEIVE AND ACCEPT NANOMATERIALS IN THE FOOD INDUSTRY COMPARED TO THE POTENTIAL RISKS ASSOCIATED WITH THESE MATERIALS?

   This research focuses on bridging the gap between consumer views and the actual risks of the nanomaterials incorporated in food, how these views are formed, and what part messages or education play. In this regard, the thesis focuses on consumer attitudes toward nanotechnology in food products and their commercialisation to highlight the related consumer needs.

ii. WHAT FACTORS INFLUENCE CONSUMER PERCEPTIONS OF NANOMATERIALS IN FOOD?

Perceptions of food nanotechnology are culturally and contextually constructed, and several factors affect the perception of nanotechnology in food products. Such factors involve awareness of or precepts about nanotechnology, cultural friendliness towards technology, and trust in the systems which control food's safety. Since demographic attributes such as age, level of education, and wealth have been established to have impacts on the perceptions of consumers, such characteristics may equally be important in the context of the present study. This sub-question pursues such understanding and analyses how the major factors that shape consumer attitudes towards the application of nanomaterials in food and acknowledges the interrelationships with the benefits and hazard perceptions of nanotechnology. It is instrumental to alleviate these challenges to enhance the acceptability of nanomaterials in the market and facilitate the efficient launch of nano-enriched food products, 'safer and healthier'.

iii. HOW DOES RISK COMMUNICATION IMPACT CONSUMER ACCEPTANCE?

Communicating the risks or benefits of innovation is essential in developing consumer perception about such high-technology foods modified by nanotechnology. This question investigates how the consumers' acceptance of the use of nanomaterials in food is influenced by the various types of risk communications – media coverage, press releases, and others, of governmental and other agencies. The research will analyse whether the level of acceptance of nano-embedded foods among consumers will be dependent on how the information on the innovations is packaged, positively or negatively. This section will further explore the need for 'trust' in information/communication sources, and how effective risk communication can enhance consumers' perception of the safety of nanotechnology within the food industry.

iv. HOW WELL DO CONSUMER PERCEPTIONS ALIGN WITH ACTUAL RISK ASSESSMENTS OF NANOMATERIALS IN FOOD?

There is often a gap between consumer perceptions of risk and the scientific risk assessment of the regulatory authorities. In exploring how well consumer concerns match the actual risk assessment of nanomaterials in food, we can discover whether consumers' concerns regarding nanomaterials are like the expert's concerns. The study will compare what people think to the outcomes of the toxicological studies and the risk assessments from the regulators to see if consumer fears are based on science. This comparison will bring out the disparities between the risk perceived by the people and the actual risk involved. An analysis of this difference will show how the communication gap or lack of education can be curtailed. The agencies that regulate the food industry assess risk from a scientific angle, but the consumer's perception can often misjudge risk for an innovative technology.

1.6 Contribution of the Study to the Relevant Literature

This study contributes to the current body of research by actively bridging the gap between scientific risk assessments of nanomaterials and stakeholders in the food industry. Most research looks at the benefits of technology and the worries of consumers as separate areas, but this thesis brings them together into one framework. It looks at how risk communication, trust in regulatory bodies, and social and cultural factors affect how people feel about nanotechnology in food, in a structured way. This study differentiates itself through its focus on the consumer's point of view, instead of just the technical or toxicological aspects. It shows how important perception, education, and openness are for the success of adopting new technologies. The thesis doesn't just look at trends; it investigates how and why those trends exist, especially by comparing how people feel about real-world regulations and science.

New value is added by doing a thorough comparison of how consumers see nanomaterials and how risky they really are, considering different industries and cultures. It shows how gaps in risk communication and regulatory clarity can make consumers less likely to trust what they hear about risks. The study gives policymakers, food technologists, and marketers who want to get more people to accept nano-enabled food products useful information by pointing out these mismatches and stressing the need for clear communication. In doing so, it not only fills a major gap in consumer-focused nanotechnology research but also sets the stage for future studies into ethical and communication-based ways to get people to adopt new technologies in the food industry.

1.7 Structure of the Thesis

This thesis is divided into eight chapters wherein the focus revolves around the key topics, which are consumer attitudes towards and the use of nanomaterials for food packaging, and how consumers' risks are managed.

Chapter 1: This chapter presents the aim, importance, and boundaries of nanomaterials application in the food sector, concentrating on end-users and the risk-pose nature. Also, the research question and research aims are briefly presented, and the method applied is outlined.

Chapter 2: This chapter lists the definitions, types, and properties of nanomaterials, presents the applications, advantages, such as better quality and longer shelf life of food in the food sector, and discusses disadvantages as well concerning health and the environment.

Chapter 3: This section delves into the historical response of the consumer to new food technologies and what they know about nanomaterials. It also analyses and explains the profile of the consumers based on factors affecting perception to include trust, education, and cultural perspective.

Chapter 4: Theoretical frameworks like TAM and TPB have been used to manage consumer behaviour in the foundation of new technologies. The chapter contrasts public perceived risk with scientific risk comprehension and focuses on risk communication and the relationship between consumer acceptance and risk.

Chapter 5: This chapter reviews areas of contradiction which exist between risk perception among consumers and what scientific risk data reveals and explicates, cross-industry and cross-regional acceptance of nanotechnology. Real-world application of these concepts is evident in the case study presented.

Chapter 6: This chapter examines the current regulations that exist for the use of nanomaterials, together with such ethical issues as transparency, labelling and CSR – do they affect the consumers' attitudes and trust?

Chapter 7: The deficiencies in the research as they are now, more concerning the long-term aspect concerning consumers' behaviour and the minority and hard-to-reach populations are detailed in this chapter. Trends and acceptance of nanotechnology in society, possibilities of future research are proposed.

Chapter 8: In the last chapter, the key findings of this study are consolidated, and the research question is answered, and economic effects, and policy guidelines with the advancement of nanotechnology in the food industry vis-a-vis the consumers' worry are given.

This thesis progresses gradually from basic nanomaterials in the food industry to an entire chapter on consumer perception, risk acceptance, and the relation between scientific knowledge and the opinion of society. Considering the main theoretical models, analysing empirical data, and acknowledging both the positive and negative influences of nanomaterials, the thesis is supposed to represent a complete picture of the barriers and the prospects of nanotechnology implementation in food processing. Each chapter is contingent upon the last and aims to explain, as an example, a changing landscape of technology, understanding in society, and regulation. In the end, this thesis will help answer the concerns humans have regarding all the presented opportunities of food technologies with nanomaterials. So, concerning the discussion within the recommendations and conclusions presented, results on the issues of informational transparency, ethics, and policy for the building of consumer confidence are discussed. Some of the conclusions brought out from this analysis cut across various categories beyond scholars and government to industry stakeholders in food, while helping to understand consumers' acceptance regarding novel technologies in food.

2. The Importance of Nanomaterials in the Food Industry

As a highly developed science, nanotechnology and its application in the food industry have come as a revolution. There is a rising use of nanomaterials in improving food safety, preservation, and developing effective means of releasing food nutrients and bioactive compounds. Nanomaterials are well-organised with a ratio of high surface area and volume, which enables their application as food packaging materials, preservatives, and food additives. The past decade has seen increasing concern and receptiveness among consumers towards healthier, safer, and environmentally friendly food products, which explains the quest for the use of nanotechnology in food manufacturing and packaging. All paper and biodegradable packaging materials embedded with nanomaterials can effectively play a dual role in reducing food waste, establishing food sanitation, and as well as food life span, which are major issues with food security and sustainability, which require global attention (de Sousa *et al.*, 2023). Innovation and usefulness of nano-enhanced food products are increasing yearly and the increase in studies shows that too.

2.1 Nanomaterials: Definition and Properties

There is a scope for defining nanomaterials as types of materials that have at least one dimension of a minimum size equal to one nanometer and a maximum size equal to one hundred nanometers. This size region endows unique physical and chemical properties, biological responses, and biological behaviours of nanomaterials different from those of bigger materials. One of the most common features of nanomaterials is that they have a high surface area-to-volume ratio that enhances their reactivity with other materials. These properties, coupled with such advances, are beneficial in the food industry, as they lead to minimum wastage of additives and increase the barrier effectiveness against the permeation of harmful substances and packaging. The small lateral dimensions of nanomaterials allow these materials to penetrate and interact closely with the components of foods, which can enhance the bio-efficacy of nutrients, enhance the safety of food and extend the shelf life of products. Further, higher strength, elasticity, and barrier characteristics attributed to nanomaterials render them applicable in other facets of the food industry (Baig *et al.*, 2021). This diversity of usage stems from the special properties of nanomaterials because of their small size.

In the realm of food technology, there is a plethora of nanotechnology applications, including their nutritional enhancement and packaging, which are capable of sensing and curbing any undesirable changes. Moving forward, all the various applications shall be explored further in the subsequent chapters. Out of 633 known nanomaterials, as many as 55 are used in agronomy and food science. Another study predicted that nanotechnology would find applications in at least 50% of all food products by 2020. The most used nanotechnological processes include the following:

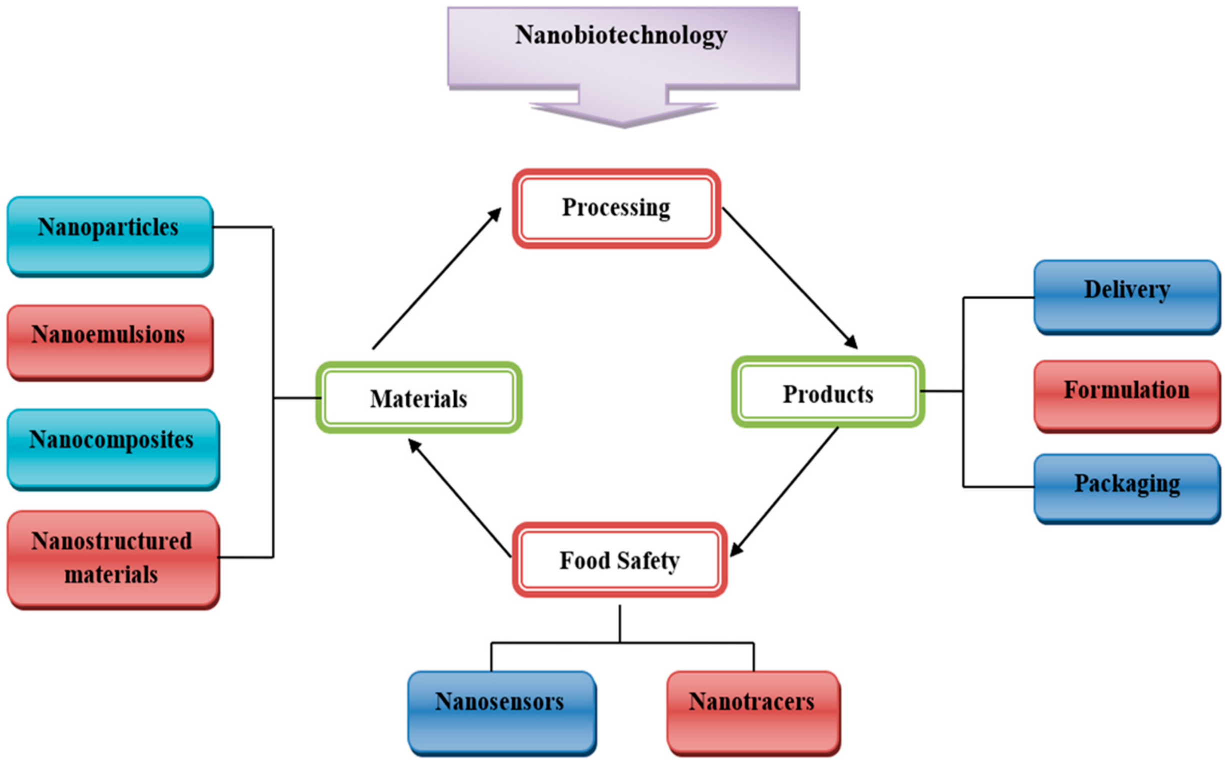

Figure 2: Role of Nanotechnology in various Sectors of the Food Industry (Shafiq et al.*, 2020a)*

- increase in food quality
- bioactive fortification
- nanocarrier encapsulation
- ability to change texture and structure of food
- intelligent packaging systems

As illustrated in Figure 2, nanobiotechnology includes a variety of options on how nanobiotechnology is positioned within different aspects of the food industry, including materials, processing, product development, and food safety. Nanobiotechnology includes the application of special materials like nanoparticles, nanoemulsions, nanocomposites and nanostructures (Shahcheraghi *et al.*, 2022). Such materials have better mechanical, thermal and anti-microbial features, which are advantageous in food processing, packaging and quality control.

The left side of the diagram is dedicated to nanomaterial applications, such as nanoparticles and nanoemulsions in food. These additives decrease the gas, moisture, and microorganisms' permeation into the raised shelf life (Dash *et al.*, 2022). For example, nanoparticles have been extensively utilised in the preparation of food package surfaces that are antimicrobial, while nanoemulsions are used to coat bioactive compounds with nutrients to target more effectively.

On the right side, the diagram displays the effect of nanotechnology on product development, such as delivery systems, formulation, and packaging. In the case of food products, it improves the bioavailability and targeted release of the nutrients and bioactive agents from the products into the body (Chen and Hu, 2020). Furthermore, nanocomposites also transformed food packaging from conventional containers to multilayer pouches and containers, which, with improved mechanical strength and barrier properties, moderate spoilage and extend shelf life, thus controlling food wastage.

The bottom part of the figure details the contribution of nanobiotechnology to food safety, particularly in respect of the nanosensors and nanotracers. Nanosensors offer an improvement in the monitoring of food safety in real time since they can monitor pathogens, spoilage indicators and other chemical threats. Such sensors are more sensitive and specific than conventional methods of detection, which ensures that potential pathogens are identified before contamination of food occurs. Nanotracers, on the other hand, enhance the food supply chain's traceability by ensuring factors including the source, treatment and safety of food products are well tracked and checked to minimise the chances of contamination and fraud (Kumar *et al.*, 2020).

2.2 Present Day usage of Nanomaterials in Food

Nanomaterials have increasingly found diverse applications within the food industry, and these mostly include the search for novel techniques to improve food quality, safety and extend shelf life. With nanotechnology and the associated increasing surface area, reactivity and barrier properties, nanomaterials are becoming highly useful in many stages of food preparation and processing (Shafiq *et al.*, 2020b). There has been a shift in recent years to include information on how nanomaterials are used in food and food objects in the focus on improvement of food packaging, nutrient delivery and even detection of contamination within food products.

Food wrappers and containers are the second most common areas where nanomaterials are utilised. More specifically, bio-nanocomposites, based on nanoclay and nanocellulose, are used to improve the protective properties of daily-use packaging materials. These nanomaterial barriers can reduce the permeability of gases and moisture, making it possible to store products like meat, fruits, and dairy for a longer period (Pires *et al.*, 2023). Additionally, incorporating metal nanoparticles such as silver and zinc oxide into the polymer packaging films provides antimicrobial activity that inhibits the growth of microorganisms and pathogens in the foodstuff (Mendes *et al.*, 2024). Such active packaging ensures the safety of the food during the entire period, including storage and distribution of the food products.

Another area of interest is the development of food additives and preservatives with enhanced functionality and stability with the help of nanomaterials. As an example, these include encasing the bioactive substances such as vitamins, antioxidants and flavouring agents into the nanocarriers. It enables the molecules to retain their integrity upon food manufacturing, storage and enhances their release and penetration into the body tissues and organs (Taouzinet *et al.*, 2023). For instance, the encapsulation of omega-3 fatty acids using nanocarriers inhibits the oxidation of the oils and stabilises their use in food formulations such as fortified drinks and dairy products, while curcumin nanoencapsulation improves solubility and absorption, hence its use as a dietary supplement (Kumar *et al.*, 2020). Nano-enhancement can not only help increase the flavour of food products but also increase the stability of nutrients that are normally fragile and difficult to digest.

Along with packaging and additives, those nanomaterials are also more and more applied in the creation of functional foods, which are products that are intended to provide health benefits more than basic nutrition. For instance, the bioactive polyphenols, vitamins and minerals from nanoparticles and nanoemulsions are more incorporated into food products in more absorbed and bioavailable forms. Nanoemulsions, which are emulsions with droplet sizes smaller than one micrometre, have been used to transform curcumin into a water-soluble form to improve the biological effect of curcumin, since so many health benefits are therefore witnessed (Pateiro *et al.*, 2021). The absorption rate of vitamins and other unstable nutrients can be enhanced to increase their health benefits.

Another area in which nanotechnology finds its critical zoom is the enhancement of food safety through the provision of nanosensors. Nanosensors are embedded in food packaging materials or within food processing facilities to monitor and respond to wastage, microbial attacks or other contamination. These sensors operate on the principle of detecting predetermined bio or chemical entities, such as chemicals responsible for toxins or gases released from decomposed foods, with a good degree of accuracy. For example, metal nanoparticles or quantum dots-based nanosensors can detect low levels of pathogens like E. coli and Salmonella within minutes, thus ensuring better food safety, as compared to the older detection systems that take hours (Kumar, Guleria and Mehta, 2017). During the storage and transportation of food products, nanosensors may be applied to track environmental factors, particularly temperature and moisture, to avoid food deterioration due to less-than-optimal conditions.

In addition, the unique properties associated with nanotechnology have been demonstrated to enhance food products, such as increasing their nutritional values and health benefits. It would be more convenient to prevent and deliver essential nutrients, which would normally be lost during processing, like vitamins or probiotics, to the consumer by using nanocarriers in food products. Nano-encapsulated nutraceuticals are more effectively absorbed by the human body, improving the health status of consumers, especially in fortified and functional foods (Otchere *et al.*, 2023). This application is useful in managing food nutritional gaps, as well as the health of the population in general.

2.2.1 Agriculture

It has been demonstrated that nanotechnology can be effectively applied in the agriculture sector, impacting the practices of agriculture and increasing yield. The incorporation of nanomaterials into agricultural systems has facilitated the invention of fertilisers, pesticides and nanosensors for soil health and plant health measurement. Such inventions allow the targeted and efficient use of nutrients and chemicals, such as pesticides and therefore lessen chemical pollution. For instance, nano-encapsulated fertilisers enhance the controlled and gradual release of nutrients, which improves plant nutrient use efficiency and reduces the loss of nutrients to leaching. Likewise, nano-pesticides are also more environmentally friendly because they can be applied to achieve a more focused pest control approach that is less harmful to non-target pest organisms. Farmers also make use of nanosensors to determine soil conditions and plant properties that aid in making appropriate decisions about water, fertiliser and pesticide use (Chhipa, 2017). Nanotechnology in agriculture not only increases crop production but also minimises agricultural adverse effects.

2.2.2 Packaging

Packaging is a crucial competitive point for which nanotechnology is being fully explored around active, smart and intelligent packaging. Barriers to gas, moisture and microbial contamination of traditional packaging materials have been improved by the incorporation of nanomaterials. Nanotechnology has revolutionised conventional packaging as one key feature, and that is the introduction of active packaging. Such packaging works as a barrier and, upon interaction with the food, causes improvement in the quality and shelf life of the food. For example, active packaging may contain antimicrobial active ingredients, such as silver or zinc oxide, which are embedded in the nanoparticle form and act to inhibit the growth of microorganisms, thus increasing the shelf life of fresh products (Shafiq *et al.*, 2020a). This indicator could prevent food spoilage and increase the health standards of food packaging.

Smart packaging makes use of nanosensors embedded in the food or the food package to measure temperatures and gases that are emitted from the food or emitted onto the food package, providing a live update on food condition. These sensors can also detect microbial and spoilage gas build-up and provide feedback in the form of a visual or electronic signal when the limits have been reached (Mustafa and Andreescu, 2018). There are also some smart packaging technologies which include strips that change in colour when the food is not fresh, helping prevent wastage in the food.

Intelligent packaging advances this concept to include nanosensors that do not merely detect spoilage of the food but also give information on the metabolic changes in the food, helping to manage the condition more accurately. The systems can evaluate infections, chemical compositional changes that occur upon inoculation of the cells while sitting on the shelf, and different conditions, for a complete approach towards food maintenance during the entire distribution process (Dodero *et al.*, 2021a). Solutions that combine active, smart, and intelligent packaging systems are likely to lower food wastage significantly while maintaining the quality and safety of food products in transit and storage for longer periods.

2.2.3 Processing

It has been realised that many developments are possible in food processing using nanotechnology. Materials such as nanospheres, nanosieves, nanoemulsions, and nanomicelles are being used to enhance food processing methods. For example, nanospheres and nanosieves can be applied in filtration and purification processes, such that unwanted particles or contaminants present in food products may be removed. As emulsifiers, oil nanoemulsions containing dispersed droplets of oils in water are added to food products to increase their texture, stability, and bioavailability of food constituents (Ashaolu, 2021). These emulsions are also useful in the preparation of functional food and beverages by aiding in the delivery of bioactive compounds, including vitamins, antioxidants and fatty acids.

Nanomicelles are another of the processing products developed through the application of nanotechnology; these target hydrophobically active components and enhance their water solubility in food products. This way, food formulations containing lipophilic nutrients can be prepared, and analogue foods made more nutritious (Li *et al.*, 2022). Overall, the use of nanotechnology in food processing increases the quality of food products regarding physical and chemical parameters, which in turn positively impacts food safety and nutritional improvement of food products.

2.2.4 Nutrition Value Enhancement

There is also an effect of nanotechnology on the nutrition of food products through the application of nanoencapsulation techniques. Nutrients or bioactive compounds are loaded in nanocarriers that store these active compounds, preventing them from being destroyed during the processing or storage of food products. This technique is especially useful when nutritional components such as vitamins, omega-3 fatty acids and probiotics that are heat, light or oxygen sensitive need to be encapsulated (Taouzinet *et al.*, 2023). Not only medicine but also food products can benefit from nanoencapsulation because food that travels a long way could retain its nutritional values.

Nanoencapsulation plays a key role in increasing the bioavailability of nutrients, hence reducing wastage by the body. For instance, when curcumin, which has anti-inflammatory and antioxidant properties, is nanoencapsulated, studies have shown that it improves solubility and absorption into the human body as opposed to the other forms that are not encapsulated. Nanocapsules that are encapsulated in each nutrient improve stability and delivery, providing a better way of tackling problems of nutrient insufficiency (Moniruzzaman *et al.*, 2024). This strategy is particularly relevant to the work on fortified and functional foods, whereby the aim is to go beyond normal nutrition and help with extra health benefits.

2.2.5 Shelf Life

Nanotechnology within the food industry plays an important role in enhancing the shelf life of food products. Packaging materials with nanocomposites and nanolaminates are developed to protect products from temperature, humidity and mechanical stresses. They prevent oxygen, moisture and light, which hastens the degradation of food products. For instance, nanolaminates, which consist of thin hills of nanoscale materials, can be coated on food or it's packaging to make them more durable and prevent spoilage (de Sousa *et al.*, 2023)(Sarfraz *et al.*, 2021). Furthermore, the addition of biosensors within packaging material can enable the detection of some environmental factors, like gases that may be a sign of spoilage or microbial activity within the food packaging. These biosensors deliver updated information concerning the period when the food is consumed, hence enabling an improvement in the management of the food quality and subsequent reduction of food waste (Mustafa and Andreescu, 2020). Nanotechnology, therefore, provides an all-around approach to extending the shelf life of foods with the prospect of enhancing food safety while promoting sustainability through averting food wastage.

2.3 Benefits of Nanomaterials in the Food Industry

First and foremost, it should be emphasised that nanotechnology provides significant advantages in food-related activities, primarily in terms of food quality improvement, shelf-life extension, and safety analysis. These improvements come because of the special characteristics which nanomaterials possess, increased surface area and reactivity, and improvement of mechanical and barrier properties, among others, which can be put to productive use in food manufacturing, packaging and preservation. Spoilage is decreased, achieved through microbial control, nutrients are better delivered, and finally, the general food quality is improved (Herrera-Rivera *et al.*, 2024).

Furthermore, through the use and exploration of the advances in the science of nanotechnology, the food industry will obtain even more sophisticated means of food alteration in the coming years.

2.3.1 Nanomaterials in Food Packaging

Nanotechnology plays an important part in designing better systems for food packaging. With the incorporation of nanocomposites in packaging materials, there has been an improvement in strength, thermal stability, as well as barrier properties. For instance, packaging materials use polymer composites that incorporate nanomaterials such as nanoclays, nanocellulose and metal oxides like titanium and zinc to enhance the packaging material's barrier to oxygen, carbon dioxide and moisture. This is essential in controlling food spoilage and shelf life. For example, the utilisation of nanoclay in polyethylene ensures that oxygen permeability is reduced by as much as fifty per cent (Sarfraz *et al.*, 2021). This has great implications, especially for the packaging of oxygen-sensitive foods such as meats and cheese.

Besides enhancing barrier properties, nanomaterials can be used in packaging with actively embedded antimicrobial systems. Silver nanoparticles have also been introduced in packaging materials to reduce the bacterial and fungal growth that causes food spoilage due to such materials' inherent antiallergic properties. Such packaging systems not only protect the food from being contaminated by external agents but also actively try to keep the food fresh for a longer period (Bruna *et al.*, 2021). By getting rid of the causes of food spoilage through efficient control strategies employing certain antimicrobials that are activated when environmental factors change, such as humidity and temperature.

Another area of substantial progress is the use of intelligent packaging systems which utilise the principles of nanotechnology to keep track of the state of the food during storage and in transit. Packaged nanosensors are sensitive to changes in parameters that surround the food, such as pH levels, gas concentrations (ethylene produced by ripening fruits), or even bacteria. Nanotechnological advancements have developed extremely small sensors that can monitor the environment or the product for signs of deterioration and thus estimate the quality of food products as needed. In some intelligent packaging systems, when food changes its quality, it also changes colour, simply and effectively preventing food from going too far beyond the freshness period (Dodero *et al.*, 2021b). Not only does this system enhance food security, but it also minimises wastage as uneaten food will not be disposed of long before it should be.

2.3.2 Nanomaterials as Preservatives

Nanomaterials play a critical role either by being incorporated directly into the food matrix or by being part of active packaging systems. Many of the positive functions of nanomaterials, such as their use as preservative agents, include the ability to make available active antimicrobial and antioxidant agents in a controlled and prolonged release, which prolongs the shelf longevity of highly perishable food products. For instance, we have nanoencapsulation, which involves the wrapping techniques of bioactive molecules like preservatives, vitamins and antioxidants in nanocarriers in which the molecules are shielded from destruction and are released slowly over a limited period (Ezhilarasi *et al.*, 2013). Due to their high antimicrobial activities, silver nanoparticles are found in food packages as well as being applied to food substances. They are more efficient as compared to other conventional preservatives because of their smaller size, which enables them to penetrate the microbial cells, hence triggering stronger antimicrobial action in less concentration. Additionally, nanocapsules or other suitable vehicles can be employed to stabilise and improve their antifungal effects by standard delivery systems like essential oils. For example, nanoencapsulated oregano oil and thyme oil were shown to have a powerful antimicrobial effect and even more so without affecting the sensory characteristics (Bruna *et al.*, 2021). Another application of nanotechnology in food preservation is in the use of nanoemulsions, which are emulsions where the dispersed droplets are nano sized. These nanoemulsions allow hydrophobic preservatives or antioxidants to be delivered and maintained over the food so that they are well incorporated into the food's components with sustained activity (Choi and McClements, 2020). The increased solubility and bioavailability of preservatives transported through nanoemulsions also increase the shelf life of food without the incorporation of high levels of synthetic additives.

2.3.3 Nanomaterials in Nutraceuticals and Food Additives

Nutraceuticals and food additives are another sector where nanotechnology has been applied, focusing on the increased health benefits of food products. Nutraceuticals are food products with pharmaceutical properties and therefore, besides nourishments, deliver bioactive substances such as vitamins, minerals, and antioxidants (Singh *et al.*, 2022). The adoption of nanotechnology in this area has led to the creation of drug carriers which enhance the delivery, stability and absorption of bioactive compounds.

Bioactive compounds can be encapsulated, such as liposomes, solid lipid nanoparticles, and polymeric nanoparticles, which serve a retarding effect on the adverse effects caused by food processing or digestion. This enhances their stability and provides the controlled release of the active ingredients, ensuring that the advantages targeted towards improving health are fully maximised. Antioxidants such as curcumin, with proven anti-inflammatory properties, have also been subject to nanoencapsulation to enhance bioavailability and solubility, enabling them to act effectively as nutraceuticals (Choi and McClements, 2020). Besides, nanotechnology is also helpful for improving the sensory properties of the food product. Such nanostructures help improve the nutritional value and visual appeal of food products by changing their texture, taste and appearance. For example, while on the other hand, it is usual for low-fat or low-sugar products to be unacceptable in terms of product texture and taste, the problem can be resolved using nanomaterials to replace the tastes of full-fat or full-sugar without adding unwanted ingredients. This is of great importance currently, as the trend moves towards healthier eating, and a more health-conscious target group is sought after (Liu *et al.*, 2019). This is of great importance currently, as the trend moves towards healthier eating, and a more health-conscious target group is sought after.

2.3.4 Nanotechnology for Food Safety

Nanotechnology provides advanced solutions towards ensuring food safety, especially regarding the novel detection techniques developed in the form of nanosensors and detection systems. Food safety is guaranteed by these nanosensors detecting foreign substances, pathogens and toxins present in foods at very low levels and hence can be described as a fast and effective means (Kumar, Guleria and Mehta, 2017). These sensors are of high importance for accurate food monitoring systems since they incorporate nanomaterials, including carbon nanotubes, quantum dots, or metal nanoparticles in their construction.

For example, nanosensors have been created for the identification of pathogenic bacteria in food, including Escherichia coli and Salmonella, significant forms of foodborne disease. It is possible to detect bacterial contamination using these sensors at very low levels, which helps to prevent the release of potentially contaminated food products in the market. Nanosensors can also work from the producers' end, especially in supplying food quality information along the food supply chain (Bobrinetskiy *et al.*, 2021). They can be used to monitor changes in environmental variables such as temperature, humidity or gas composition to ensure that food is kept and transported under the right conditions

The integration of nanosensors into the "smart" packaging brings about new ways of ensuring food safety. These solutions can communicate the current product sitting on the shelf in terms of its freshness or spoilage, and this will help in the preventive measures of the food's safety. Moreover, smart packaging technologies can extend the shelf life of food products and minimise food waste (Guruprasath *et al.*, 2024). They ensure food is rarely thrown away due to the uncertainties of its freshness being eliminated.

2.4. Potential Impacts of Nanomaterials on Food

Food, as one of the industries where nanomaterials are employed, has its merits such as improving food quality, safety and extending shelf life, but such application also comes with risks that need to be addressed thoroughly. These health concerns are justified due to the small particle size and great reactivity of nanomaterials, as these can cross biological barriers and interact with cells in ways that cannot be achieved with traditional materials. These health risks include, for example, the possibility that nanoparticles might be absorbed by the body's circulatory system from food and might even get lodged inside tissues over time. Thus, scholars have warned about the hazards of some food additives and nano-packaging, for instance, silver and titanium dioxide, which are generally added to food preparations. Since such materials expose human cells to oxidative agents, stimulation of the cells for excessive periods can lead to adverse effects like inflammation, tissue destruction and can result in cancer cases (Guruprasath *et al.*, 2024)(Vieira *et al.*, 2022). However, these questions require more scoping research and more time to resolve the issues surrounding the intake of nanomaterials from food and their residues from food substances.

Environmental concerns are yet another risk but are intensified when nanomaterials are wasted through food package disposal or from food process operations. Some of these nanoparticles are toxic, like silver and zinc oxide, and are bioactive in soil and water ecosystems; hence, they upset ecological cycles and may bio-magnify. Low degradation of these nanomaterials in the environment justifies concerns about the bioaccumulation of such materials in plants and animals, and eventually in the human food chain (Beegam *et al.*, 2016). Such concerns highlight the importance of effective policies and controls relating to nanomaterials to avert unintended harm to the environment.

Apart from the health and environmental arguments, ethical issues come into play regarding openness and the consciousness of the consumers. Many foods that incorporate nanomaterials are sold without any notice on the packaging template to help in labelling, thus, consumers have no idea what they are eating. Lack of such information can affect the level of confidence that consumers have in the products and brings serious implications on democratic principles of free will, informed consent, and the right to know what is inside one's meal. Moreover, it is feared that vertical integration due to cutting-edge nanotechnological applications in the food sector would increase inequalities (Hasmin *et al.*, 2021). Big corporations benefit the most from new technologies, while small-scale producers mostly cannot cope with the pace of adoption. As the understanding of the toxicology of nanomaterials improves, regulatory bodies such as the European Food Safety Authority (EFSA) are developing the conditions for safe operation with them to prevent any trade-off from the application of nanotechnology to human health and the environment.

2.5. Health and Environmental Risks from Nanoparticles

The primary health risks of nanomaterials in food products arise due to the nanoscale properties focused on critical interaction with biological systems. Because of their minimal size, these nanomaterials can cross biological barriers and reach the bloodstream through the internal wall of the intestines and may hence settle in certain tissues and even organs. There has been a rising concern regarding the safety of certain nanomaterials, such as nano silver and nano titanium dioxide, that are used widely in food products and food packaging. These nanoparticles could lead to the release of reactive oxygen species (ROS) that could be toxic and result in stress, inflammation, and cytotoxicity (Usmani *et al.*, 2024). Sustained exposure to these particles, among other health risks, may lead to organ damage, immune dysfunction, increased susceptibility to chronic diseases or possibly the development of cancer.

In addition, it has been established that this practice exposes patients to unknown risks for an extended duration. Some authors have shown that, in short-term studies of a few weeks, no inflammation of the respiratory tract tissues is observed, still significant toxicity is induced by the nanoparticles. In contrast, there is some evidence indicating that some nanomaterials might pose different health effects at varying concentrations, i.e. less toxic at lower concentrations than at higher levels. Biological toxicity caused by nanomaterials can remain in the body and bioaccumulate over time, potentially leading to long-term health effects (Haase *et al.*, 2024). Therefore, developing the ideal safety for this technology or considering and managing potential risks in the credibility and effectiveness of nanomaterial safety should be approached cautiously, rather than seeking immediate commercial benefits.

Toxiclogy Effects of Nanomaterials on Animals (Mice & Fish)

Nanomaterial	Dose	Duration	Observation
CuO	400 mg/kg	4 weeks	Caused damage to liver and kidneys.
Silver	15 mg/kg or 30 mg/kg	7 days	High doses caused kidney structure changes.
CuO	25 – 200 µg/mL	24 – 96 hpf	Led to deformities and delayed development in embryos.
Chitin	100 – 1000 µg/mL	10 – 60 min	No toxic effect observed.
ZnO	35 or 105 mg/kg	21 days	Reduced body weight and caused gut tissue changes.
Zinc Oxide	50 µg/mL	96 h	Digestive malformations in aquatic organisms.
Titanium Dioxide	25–200 µg/mL	24 h	No toxic effect on healthy or cancer cell lines.
Zinc Oxide	5 mg/kg b. wt/day	6 weeks	Caused liver and kidney damage.
Silica	10, 50, 100 mg/kg	24 h	No visible damage in organs.
Chitosan	20µL	7 days	Caused kidney infection.
Iron Oxide	0.25, 0.5 µM	48 h	Led to heart failure in fish.
CuO	25 mg/kg	14 days	Affected male reproductive organs and increased cell death.
Polystyrene	150 µg/mL	24 h	Decreased cell survival in lab-grown cells.
Non-porous & mesoporous amorphous Silica	100 or 1000 mg/kg	5 days	No toxic effects found.
Graphene Oxide	2 or 5 mg/kg	5 days	No effect on movement.
Titanium Dioxide	50 and 250 mg/kg/day	28 days	Reduced sperm cells and caused testicular damage.

Figure 3: Toxicological Effects of Nanoparticles (Gupta, Guha and Srivastav, 2024)

The data presented in Figure 3 shows the dose levels of nanoparticles which have been administered for toxicity studies in different biological models. The most important data points from the original table have been taken to represent one specific material and dose, thus, the diversity of the experiments is presented. Tests of the chitin and the non-porous silica are done at the highest doses of up to 1000 mg/kg, mainly in mice. Titanium dioxide (TiO_2) and CuO nanoparticles were tested at high experimental doses, especially in zebrafish embryos and rats. The study on zinc oxide (ZnO) was done on different organisms, including rats, fish and mice, with a dose of up to 105 mg/kg. Silver, graphene oxide, and iron oxide nanoparticles were given at a low dose in most cases, less than 30 mg/kg. This table illustrates the variation in testing conditions and helps contextualise how nanoparticle dose and biological systems influence toxicity assessments.

Nanomaterials used in producing food could pose other equally nevertheless, dire environmental issues environment related. More notably, about their disposal or biodegradation. Throwing away food packages containing nanotechnology in any landfill or area with water may lead to contact with the nano-infused food product. Urbanisation results in pollution and the quick distribution of foreign substances that hamper previously complex niches in the ecosystem. When nanoparticles are put into the environment, deposition takes place on soils and water bodies, and this could affect the animal and plant life present in those water bodies (Walters, Pool and Somerset, 2014). Some percentage of silver nanoparticles were found intracellularly, and these are cytotoxic to microorganisms and aquatic organisms by affecting cell respiration and reproduction.

It is also a matter of great concern for its long-term survival in the environment. Nanomaterials are durable and long-lasting, unlike bigger particles that eventually break down to cause pollution. Concern is raised over their long-term presence and incorporation in the food chain, where they could harm animals and humans alike. For example, there is a good chance that nanoparticles will end up back in the food chain. In that case, they either become part of the structure of plants or are consumed by animals [54]. The safety worries about eating food possibly containing nanomaterials add urgency to devising improved management strategies for nanomaterials in food systems if these materials.

3. Consumer Perception of Nanomaterials in Food

Food technologies that incorporate nanomaterials, which can be considered advanced techniques, face many challenges among consumers. Trust, familiarity, influence from the media, and individual values are some of the factors that shape these consumers' perceptions of food technologies. The functions of nanomaterials in food products include quality enhancement, safety, and preservation of food products, however, the consumption of such products depends on the consumer’s view of their safety and utility. Although it looks well, especially for the sectoral economy, in that almost every food item can be applied, this has stirred so much controversy, mostly due to general ignorance by the public on the issue and concerns about their safety in the future. (Kuang *et al.*, 2020). Not only will this chapter address how consumers perceive the application of nanotechnology in food, but it will also compare with how consumers behave about other new food technologies like GMOs and food irradiation. These changes suggest that similar factors may affect consumers’ views towards nanomaterials in food.

The perception of new technologies such as nanotechnology in the food industry is largely dependent on the awareness and knowledge of the consumers. However, it remains a vague, hard-to-grasp technology for most consumers, oftentimes leading to negative attitudes or aversion to its application in food products. This is fuelled by the fact that when faced with a new technology, consumers are more likely to concentrate on what dangers the technology presents as opposed to the advantages of it (Siegrist and Hartmann, 2020). It is noted in previous studies that without adequate information about nanotechnology, most consumers shift their attention to possible problems (i.e. health and environmental or cultural risks) as opposed to possible advantages (i.e. safer food or longer food shelf life).

In addition, educating consumers helps in narrowing the differences between the risks and their expectations. The level of acceptance among consumers of nanotechnology, for instance, appears to rise when consumers are made aware of its specific benefits, like improvement in food quality and safety through nanosensors and reduction of wastage. Siegrist et al. (2020) also informed on the fact that communicable understanding and awareness are essential to address issues of consumer rejection of maladies concerning nanotechnologies. The research findings indicate that consumers who recognise and comprehend nanotechnology are inclined to derive positive perceptions and accept the utilisation of nanotechnology in food products. The survey further stresses the need to educate the public on nanomaterials and their safety, as well as actively engage in public education about the benefits of nanomaterials to counter negative views, to increase acceptance by the market (Siegrist and Hartmann, 2020). Building trust through public education initiatives is required to encourage the acceptance of nano-food products by consumers.

Apart from these, the media also has a great influence on the way that consumers perceive products. There is the choice of stimulating the anxiety associated with new technologies by emphasising their possible threats or instead raising the people's trust by stressing the structure of safety measures and protective and useful aspects of the technology. For example, the media reporting on the invasive safety assessment and regulation of nano-food will do more to instil confidence in public rationality rather than an outcry (Siddiqui *et al.*, 2022). Such reports mostly emphasise negative ethical aspects and do not illustrate the available data and policy measures; thus, they might raise distrust

3.1 Past Consumers' Views and Concerns on Novel Food Technologies

Looking at consumers' attitudes toward other novel food revolutions and their issues, like GMOs, food additives and irradiation, is worthwhile. Often, GMO food or genetically engineered food suffers from this kind of undue criticism when it reaches the market. Furthermore, such a technology becomes a cause of concern mainly due to the safety and ethics of such technology. Also, the limited knowledge of the ways to use such technology causes this kind of concern and criticism. Since the introduction of new technologies, they have encountered hostility, but overall, their criticism is warranted. Be it for the sake of getting regulatory bodies on par with the advancements to analyse their risks and minimise them for the public. However, their acceptance into the market relies on several factors, most notably risk/benefit, trust in authorities for food safety, and information provided by the supply chain.

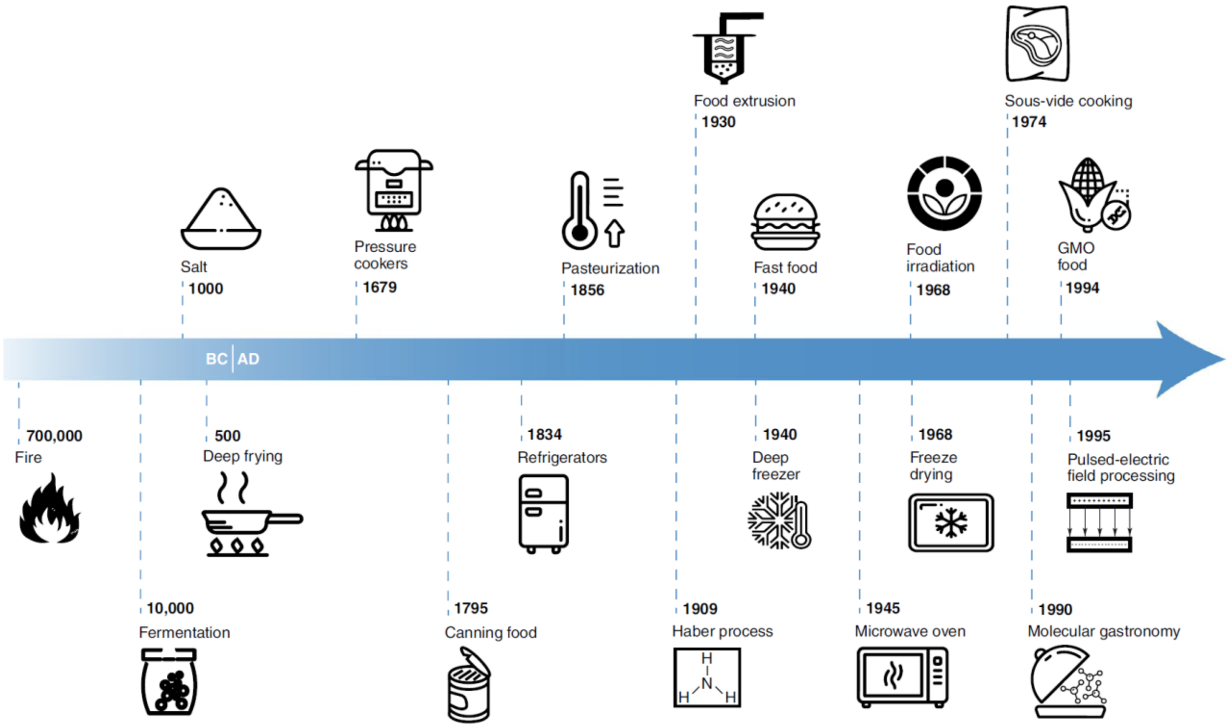

Figure 4: Timeline of Novel Food Technologies (Siegrist and Hartmann, 2020)

For instance, the issue of GMOs quickly raised a great deal of adverse attention, particularly in Europe, where the ethical considerations of 'playing God' and adverse health issues were all the rage. (Siegrist and Hartmann, 2020). Even though science and political reasoning justify the existence of GMOs in the current society, the development of new crops, and how expanding agriculture can be efficient in solving food deficiency, the people's response was not very pleasant anyway. As the people became more educated about the safety measures taken on the use of genetically modified foods and the regulation of their communication, there was a positive turn of events. (Bašinskienė and Šeinauskienė, 2021). Such learning patterns reinforce the strong impact of education on reducing risk perception towards food technologies.

The use of other foreign substances termed as food preservatives was met with a challenge that was concerned with the health risks of such synthetic additives. People considered preservatives to be artificial and were thus apprehensive about using them for a period. However, as people got used to the fact that preservatives decrease the rate at which food or other products are spoiled, the suspicion reduced (Peng, 2023). This change demonstrates that there are situations when education and familiarity with a technology decrease the initial resistance towards it and enable its acceptance.

The analogy of nanomaterials arises because it brings to the fore a recurring pattern of sensitivity among consumers towards novel food technologies: novelty and perceived danger define the first instinctive reaction. In many situations, it is the consumers' fear of self-perceived risks, which were further exacerbated by the media and lack of clear communication, that resulted in a low rate of adoption of these new technologies. As illustrated with GMOs and preservatives, adopting new technologies is often easier when people have first become familiar with how they work and what good new technologies are likely to do. Nanomaterials in food are likely to undergo a similar overall path. At the outset, there is likely to be some scepticism on account of the unknown danger to health and the environment. However, as has been the case with earlier technologies, the adoption of nanomaterials by consumers will be balanced on the degree of public confidence in the regulatory agencies and the ease of getting sufficient information on their safety and benefits (Zhao, Yue and Kuzma, 2020). Comfortable levels of nanotechnology, with the improvement of literacy among consumers, would lead to less risk perception and hence expansion in acceptance of applications of nanotechnology.

3.1.1. Analysis of consumer attitudes regarding GMOs, Preservatives, and Food Irradiation

The future of GMO foods, preservatives and food irradiation followed a similar pattern where attitudes have been negative at the beginning and have moved to the positive end more because of education and regulations that have been put up. GMOs and food irradiation attract high public opposition, especially in Europe, where the unnatural manipulation of one's genes and threats to the ecosystem are the main concerns. An intense focus on consumer education on food security issues has produced a high level of acceptance in the U.S. and developing countries, such as Brazil and India (Siegrist and Hartmann, 2020),(Sadikiel Mmbando, 2024). Fostering transparent communication and targeted educational initiatives is crucial for building trust and encouraging informed acceptance of nanotechnology in the food sector.

The U.S. allowed preservatives once they were accepted as food security, whereas preservatives were viewed as a health hazard. Europe, on the other hand, had a major shift towards clean-label trends, which refers to a shift towards using natural additives (Khunsee, Kaewsritong and Srikaeo, 2024). Food irradiation is scientifically justified but controversial. In Europe, there is a lot of cultural resistance to processes, which people view as 'unnatural. This is simply another example of how difficult consumer perceptions are to change after years spent forming them (Bearth and Siegrist, 2019). This is yet another evidence of how difficult it is to shift the perceptions of consumers after a long time spent forming them.

3.1.1.1. GMOs: Variations by Region and Culture

In the most researched new food technology, consumer perceptions of GMOs differ depending on geographic and cultural perspectives. GMOs made their US debut in the 1990s but were not met with much opposition at that time. This is because of the high level of trust that the people had in the U.S. Food and Drug Administration (FDA) and the U.S. Government. The U.S. Department of Agriculture (USDA) and FDA regarded GMOs as useful and practical ways to enhance farming production and ensure the safety of food and drugs. Most people in the United States grew to accept these assertions while ad campaigns sought to present GMOs in a positive light, claiming things like higher yield, as well as pest-resistant crops. This thinking appealed to people mostly concerned with how much food would cost and how much of it could be produced, not with threats (Siegrist and Hartmann, 2020). In areas where consumers have more doubts about regulators and more emphasis on naturalness, the opposite is true, suggesting how institutional trust and communication help shape public acceptance of new food technologies.

European consumers were previously more reluctant to adopt genetically modified organisms than American consumers. This is because they think of food as requiring naturalness, are strongly sullied by authorities who push GMOs, and are generally sceptical of scientists. Within the EU, policy mechanisms guided by the precautionary principle have much stricter rules than those present in the US. All concerns of European consumers, which are based on environmental concerns, ethical issues, and future risks, have led to the complete rejection of GMOs. The press and media began to emphasise any potential harmfulness rather than letting the scientific community defend safety by upholding information. In Europe, legally required product labelling of any GMO is used, and the difficult process to obtain the authorisations has been implemented. Which has amplified negative public opinion, but did meet the information transparency needs of the public (Woźniak-Gientka, Tyczewska and Twardowski, 2022) The European response embodies a historical request for transparency and control, characterised by public scepticism, cautious regulators, and a selective mass media, which leads to an ingrained resistance against GMOs.

The responses to genetically modified organisms (GMOs) from developing countries have been more mixed, and differences have been manifested due to local food security needs and socio-political conditions, which remain determinants. Countries like India and Brazil, where GMOs have been projected as a means of raising production and combating hunger, have received some level of popular support. However, in other continents, particularly Africa, the uptake of GMOs has been slow. This has been a result of a combination of politics, fear of multinationals monopolising seeds, and worries about potential negative environmental impacts. Public education on the effectiveness of GMOs in these countries is lacking, which causes GMO scepticism (Sadikiel Mmbando, 2024). The extent to which developing countries adopt GMOs primarily based on food security is dependent on political power and understanding of the technology.

3.1.1.2. Consumer Responses to Preservatives: Perceived Safety and Naturalness

People's attitudes regarding food preservatives, especially synthetic ones, differ depending on the region's perception of food safety and naturalness. In the U.S. and most developed nations, the use of food preservatives is usually a matter of controversy; however, in most situations, the use of them has been tolerated for various reasons, like prolonging their shelf life and providing protection against foodborne and spoilage diseases. In these areas, the consumers search for convenience and thus accept these preservatives more and more. This is especially true when it is offered with the view that it is necessary for the safety of food. Likewise, affordability will also lead to the acceptance of these products. These patterns are nearly universal in the regions, as the regulatory authorities are in favour of the usage of preservatives. They claim their safety after thorough tests for extensive usage, which has enhanced the public's confidence (Rathee *et al.*, 2023). This example shows how trust in regulatory authorities and the value given to convenience can affect the acceptability of novel food technologies.

Most images of traditional synthetic preservatives made from petroleum products are presented under the denomination of chemicals. However, people in societies and geopolitical regions where people practice a natural food culture and where the organic food movement philosophy is of high dynamics, resisted the synthetic preservatives more. Countries such as Germany have a phobia of synthetic preservatives. Due to some scepticism among consumers, preservatives were also considered something strange and unhealthy. People give a higher value to clean and high-quality foods. People also prefer to eat more fresh foods instead of processed foods. Regulatory responses in the region have seen increased demand for "clean label" products (free from synthetic additives). Additionally, the focus on self-explanatory product packaging has assisted market growth towards the acceptance of natural means of preservation (Chang and Chen, 2022). Regulatory responses in these regions are witnessing more demand for "clean label" products (that do not contain any synthetic additives). The focus on self-explanatory packaging has prompted the market to grow towards accepting natural means of preservation.

In less developed nations, there's a more pragmatic perspective, which sees food additives as preservatives to prevent spoilage and provide access to nutritious food in the less developed parts where refrigeration and other means of keeping food fresh may be difficult. Yet, even when food insecurity is still an issue, the larger exposure to health and environmental issues comes with more fear of the regular usage of such artificial additives. Consequently, people increasingly prefer to seek natural preservatives instead. The belief is that they are healthier and more eco-friendly but are more expensive and harder to come by (Rathee *et al.*, 2023). Growing recognition of health and environmental issues is beginning to change the mindset of people and create demand and policy in places where preservation is still necessary.

3.1.1.3. Food Irradiation: A Case of Extreme Polarisation

The use of ionising radiation to inactivate nutrients and microorganisms in food and to extend shelf life is known as food irradiation. It should be noted that this technology has been received differently depending on the part of the world. In the U.S.A., food irradiation is widely approved for use, especially in situations that are critical for the risk of foodborne illnesses, such as the meat and poultry industries. Public health initiatives, well supported by scientific evidence, have promoted the high efficacy and safety of using irradiation to kill pathogens associated with food, which has increased acceptance among customers of irradiation. Some sectors of the American public still suspect irradiated food contains nuclear waste and may cause radiation poisoning, although it is well-known to be harmless because of evidence on proper usage and safety of those foods (Parrella *et al.*, 2023). This enduring scepticism emphasises the significance of public perception and misinformation in influencing consumer acceptance, even in cases where the scientific consensus endorses the safety and effectiveness of the technology.

In Europe, food irradiation has faced much more vehement opposition. European consumers tend to prefer what is more natural and hence are more likely to be averse to technologies that are deemed artificial or harmful, just as is the case with GMOs. While the European Food Safety Authority (EFSA) and other scientific authorities approved food irradiation, the public remains unconvinced, therefore, the practice is less common than in America. Europe has regulatory provisions that make it illegal to advertise foods that have been irradiated unless there is a label is added. People who are against processed foods also feel uncomfortable towards using irradiated foods (Natividade, Alonso and Mesquita, 2023). The Europeans and their cultural longing for naturalness, as well as strict regulatory labelling, restrain the irradiation of foods.

Food irradiation is still not extensively used in developing countries, but where it has been adopted, it has repeatedly been linked to improving food security as well as reducing waste. Especially in places where there is no refrigeration available. Despite their potential benefits, many areas still face substantial resistance to these technologies. For example, some local communities do not want irradiated food due to perceived health risks, environmental concerns, and lack of information about the technology's safety and benefits (Muhammad Ahmad Muneeb *et al.*, 2023). Ongoing resistance to these technologies highlights the urgent need for public education and transparent communication to bridge the gap between technology's potential and consumer acceptance in developing countries.

3.1.2. Consumer literacy about nanomaterials in Food

The use of nanotechnology in food production and packaging, as well as food preservation, has given rise to many innovations, but on the consumer side, compliance with understanding and awareness of the use of nanomaterials in food products is still low. The applications of nanotechnology in food are relatively new, but already, there are many novel innovations in food or food packaging and food preservation. However, consumers are still less willing to have nanomaterials in food products. Research indicates that due to these concerns, a significant number of men and women believe that nanotechnology will inevitably pose a threat to our lives in every aspect (Ranjha *et al.*, 2022). The perception gap underscores the need for transparency and education to build public trust in the food industry's use of nanotechnology, emphasising the importance of regulatory frameworks and safety assessments.

An important issue regarding the use of these technologies is that a large percentage of consumers do not even know that many nanomaterials are present in their everyday products, including food. According to research by Gmoshinski et. al. 2018, over 90% of edible films made of nano-properties or edible formulations containing silver nanoparticles and nanoencapsulated particles are used in food and food packaging. Most consumers lack adequate information that can help them evaluate the risks and benefits of these nano products (Gmoshinski, Shipelin and Khotimchenko, 2018). Consumer ignorance regarding nanotechnology can exist, but they still consume it unknowingly.

Labelling could help, but it is not uniform, and because nano-scale substances are complex, it is difficult to provide information to consumers about whether food products use nanotechnology. This is changing, especially in the EU, where laws are requiring manufacturers to label products containing nanoscale materials. Noting that unless there's enough consumer education on the matter, even these will not suffice to bring confidence in the safety of the innovations (Contado, 2015). There is a need for both clarification about labelling requirements as well as consumer education, so that these innovators may not be the only thing needed to inspire confidence in safety.

3.1.3. Information asymmetry and its effects

There are great difficulties when it comes to bridging the chasm between scientific apprehensions and the knowledge that people acquire concerning new and emerging technologies, such as the use of nanomaterials in food. This disparity is often termed "information asymmetry." One party (in this instance, the scientists and the manufacturers) has more or better information than the other party (the consumers) in any transactional activity (Socoliuc *et al.*, 2022). This type of asymmetry is quite common in emerging markets, where new products or services are often unknown to the consumers, and the latter may not be well informed to understand the risks and prospects involved

A major problem with this information gap is that people are relying on what the media presents to them, so they do not bother searching for accurate information themselves. This is unfortunate because the coverage of such issues is usually characterised by a sensational tone, which tends to distort risk perception. If such scientific subjects as the application of nanotechnology in food are presented in distorted, incomplete or extreme language, it is possible that consumers' use of nanotechnology would be grossly exaggerated with fear of risks (YAN *et al.*, 2019). Such scenarios can enhance negative public perception towards novel technology, which should instead be beneficial in promoting the quality and safety of novel food products.

Educating consumers on the basics of science is crucial in alleviating the fears that most people have regarding nanotechnology. Where consumers have some understanding of the scientific concepts, their perception of risks and opportunities is much better. The studies indicate that the more consumers understand nanotechnology, the lower their associated risk evaluation because of being able to grasp the comparisons with accuracy rather than widespread hysteria about the technology (Larsson, Jansson and Boholm, 2019). The communication of science and the public will help consumers to have a balanced view of the benefits and risks of nanotechnology in food.

3.1.4. Public misperceptions and misinformation

There have always been public misunderstandings and false news that have been blamed for the fears created about new technologies. Nanotechnology, especially food-related applications, is not spared from this misperception either. Quite a bit of the fear of the use of nanomaterials in food parallels whatever woes exist for genetically altered organisms (GMOs). Traditional and social media have instigated these fears by disseminating false information concerning the use of nanomaterials in food. Social networks come as a major contributor to this misinformation, as this kind of information easily spreads without control (Bode, Vraga and Tully, 2021). Such cases only raise concern when unsubstantiated claims of extraordinary proportions sweep through the web, drowning valid criticism.

In examining GMOs, it has been established that misinformation has played a detrimental role in informing consumers about GMOs. Sensational headlines worthy of Tabloids regarding the potential health hazards of GM foods have made a lot of people say no to GM foods when they are meant to solve world food problems (Lynas, Adams and Conrow, 2022). Nanotechnology likely has the same mechanisms. Nanotoxicity and contamination due to nanomaterials are examples of health risk claims that are exaggerated. Such fears and the undesired public might arise because of founded misconceptions about nanomedicine. This problem is made worse by low levels of scientific understanding in the general population, which makes it even more challenging for the public to separate fact and fiction.

Media, concerning the perception of nanotechnology, play two roles. It tends to not only serve the purposes of education but can also confuse when sensational rather than accurate content is driven by the media. In their endeavours to summarise how media coverage affects public perception of new technologies, researchers have highlighted that negative media framing and misinformation encourage risk overestimation or neglect (Kuttschreuter and Hilverda, 2019). Such framings of media views on the development of nanotechnology might delay the potential benefits that come with its application in food packaging and preservation using nanomaterials.

Nanotechnology in the food industry has been largely perceived through the lens of media coverage, and that has shaped consumers' views on the food products in question. Selective exposure to negative images of certain media fuels consumer scepticism because common sense posits that more risks are involved. In their study, Huang et al. (2020) observed that when subjected to exposure to negative nanotechnology media coverage, consumers tended to reject the technology even when science had proved it to be safe (Huang, Bai and Gong, 2020).

It is important to note that the media can also provide education and transparency regarding the safety and advantages of using nanotechnology. Effective campaigns that seek to let the public know how nanotechnology enhances the safety of food, increases its shelf life and makes it more environmentally friendly can also improve public perception of the technology. Research indicates that consumer sentiments towards nanotechnology become more positive when mass media reports objectively provide evidence to support their claims (Feindt and Poortvliet, 2020). As such, the public sees nanotechnology as a benefactor, contributing to a wider acceptance of nanotechnology integration in food products.

3.1.5. Case studies of successful public education campaigns

Food Technologies under development today are at times novel to the consumer, hence the use of such campaigns as public education campaigns has proven to be of great essence in winning the confidence of the consumer. These involve focusing on transparency, addressing consumers, and explaining the efficiency and safety of the technologies. A few case studies from past food technologies could help us understand how nanotechnology could be promoted.

The campaigns associated with gene technology and food irradiation, for instance, were able to make people accept those technologies by dispelling misunderstandings and by appealing to the natural advantages of those technologies. Transparency in communicating new facts and portraying the technology as an invention in solving the issues of food security and sustainability were among the factors that contributed to consumer acceptance (Siegrist and Hartmann, 2020). It was found that such communication improved acceptance of the technology by gaining trust and being associated with issues consumers value, such as health, sustainability, and technology.

Educational approaches must gain consumer trust in new food technologies, and it has been noted that these approaches have succeeded in various regions through targeted messages. One prime example is the Change4Life campaign, which occurred in the UK regarding the risk of obesity and aims to improve standard food choices and other diet-related practices. Various communication and media strategies were used in the campaign, such as TV, social networks and community interaction platforms (Goodman *et al.*, 2021). Simplistic and practical examples enabled the campaign to shift people's opinions about healthy eating and exercising to healthy behaviours in a broader population.

More recently, the acceptance and use of Genetically Modified Organisms (GMOs) have gradually improved in the EU and the U.S., the reason being informational campaigns and legal evolution. One recent case study has reported that concern about GMOs in the European Union has gone down rather significantly, with the proportion of citizens concerned about GMOs declining from 63% in 2005 to 27% in 2019. This change in the perception of the public has been explained by a better perception of the advantages as well as the safety of GMOs in combating food insecurity and sustainability issues (Ichim, 2021). The declining public concern has further prompted calls for the removal of regulatory restrictions that have hindered the evaluation and eventual commercialisation of GMOs in the EU, resonating with America's less hostile stance towards that technology outlook. The positive public perception demonstrated during the campaigns indicates that any further public campaign to promote the use of nanotechnology in food should concentrate on openness, educating consumers and marketing the benefits of technology with things that the consumers value, such as health and environmental sustainability. Through effective communication and confidence-building, the acceptance of nanotechnology in the food sector will probably be extended.

3.2. Factors Affecting Consumer Perception

The consumer perception towards nanotechnology in the food sector is influenced by trust and familiarity, demographic characteristics and consumer scepticism. Consumer view on nanotechnology is affected by trust. Consumers look at regulatory authorities, food producers and scientific bodies for technological risks. According to Feindt and Poortvliet (2020), consumers will respond more positively to nanotechnology if the technology's purpose is perceived to be positive and specific safety standards are clear. When authorities and manufacturers open, stressing public interests over profit, consumer trust and acceptance increase (Feindt and Poortvliet, 2020), (Meijer *et al.*, 2021). On the other hand, the perception that profit takes priority over health lowers consumer trust (Meijer *et al.*, 2021). These dynamics show that trust can be increased through transparency, accountability, and clear public benefit from authorities and manufacturers; that basically, we are not going here to make a profit.

Familiarity and exposure are also critical. Consumers who already have knowledge or experience from other industries, like cosmetics or medicine, are more accepting of nanotechnology in food products. As demonstrated by Zhao et al. (2020), informed consumers who are aware of the advantages of nanopackaging are more intent to purchase these products. Thus, disseminating information has proved effective in changing risk perception (Zhao, Yue and Kuzma, 2020). When there is not enough information available and the media emphasises the dangers, it leads to increased scepticism (Rai *et al.*, 2023). This suggests that ways to increase consumer familiarity with nanotechnology, such as positive media coverage and easily accessible information, can mitigate scepticism and give rise to an inclination towards nanotechnology in food.

Demographic characteristics further moderate perceptions. Younger and better-educated consumers typically show higher acceptance levels of novel food innovations. Higher education equips consumers with the ability to assess the benefits and risks of nanotechnology more effectively. Cultural differences are noteworthy; Asian consumers often display greater trust in new food technologies compared to their more sceptical Western counterparts (Meijer *et al.*, 2021). Asian consumers tend to be more trusting of novel technologies in food. Personalised communication strategies are important for consumer acceptance of nanotechnology in food, and this is because of educational, age, and regional factors.

The negative attitude toward food neophobia creates hurdles. According to Siegrist and Hartmann (2020), food neophobia is a prominent psychological barrier that can deter consumers from accepting new food technologies, especially if they are novel (Siegrist and Hartmann, 2020). Educational initiatives and interactive demonstrations reduce neophobia, enhancing technology acceptance.

3.2.1 Research on Consumer Perspectives Regarding Nanotechnology in Food Products

Studies show consumer attitudes towards nanotechnology depend on their sense of understanding, risk communication transparency, and regulations. Consumer education fosters acceptance and promotes readiness for the technology, as well as clear communication from regulatory bodies is recommended by Siegrist and Hartmann (2020) (Siegrist and Hartmann, 2020). Studies show that negative media portrayals lead to more consumer resistance, but positive safety and benefit narratives can help build trust (Murphy *et al.*, 2022) Cummings et al. (2021) say that the public attitude is mixed, people are still cautious despite the optimistic potential of nanotechnology in healthcare and environmental protection (Cummings *et al.*, 2021). Many people are worried about eating nanoparticles, losing control and negative side effects. According to Hasmin et al. (2020), there is confidence in regulatory effectiveness, which influences whether consumers will accept the product (Hasmin *et al.*, 2020). Findings indicate that informed understanding and positive attitudes of consumers towards nanotechnology in food can be achieved through transparent regulation, consistent risk communication, and balanced media representation.

Economic studies reflect similar findings. According to Wu et al. (2021) and Sousa et al. (2023), consumers like applications, such as food packaging used in conjunction with food materials rather than direct application as a food ingredient, presumably because of the clear utility and strict regulation (Wu *et al.*, 2021), (de Sousa *et al.*, 2023) Zhou and Hu (2018) imply that consumers have a low willingness-to-pay (WTP) for nano-enhanced ingredients as they see long-term health risks associated with them (Zhou and Hu, 2018). Transparency about health effects can lower consumers' willingness to pay as they become wary despite evidence of benefits. Consumers often have a higher willingness-to-pay (WTP) for "nano-outside" applications, like in packaging, that enhance safety but are not ingested directly (Bieberstein *et al.*, 2013), (Henchion *et al.*, 2019). This means that customers are more likely to accept a product and pay for it if there are fewer chances of being exposed to it, or less likely to absorb it.

3.2.2 Longitudinal Studies on Changing Attitudes

Longitudinal studies demonstrate a growing consumer acceptance as efforts to manage risks improve and risk communication develops. Siegrist and Hartmann (2020) similarly observed that clearer communication of nutrition and environmental benefits reduces opposing stances in Europe and America (Siegrist and Hartmann, 2020). Van Giesen et al. (2018) found that when consumers are informed and familiar, their emotional fear-based responses diminish in intensity (van Giesen, Fischer and van Trijp, 2018). On the other hand, fear remains high in places that are not regulated overly actively (e.g. by legislation) and/or are negatively portrayed in the media. A lack of trust in government is often a major problem here (Zhao, Yue and Kuzma, 2020). Frewer et al. (2014) further highlight that transparency of regulations and clear descriptions both empower society to become confident and accepting over time (Frewer *et al.*, 2014). Transparent communication, educational support, and a robust regulatory framework are crucial for managing consumer perceptions and enhancing the acceptability of applications of nanotechnology in food.

4. Risk Perception and Acceptance of Nanomaterials in Food

Key to their effective uptake is comprehension of consumers' perceptions of risk related to food nanomaterials. The perception of risks differs significantly between food applications and packaging applications. Regarding consumers' perception of risk to novel food and food packaging applications of nanomaterials is very related to emotion, especially disgust and fear. Monaco and colleagues (2024) claim that the leading causes of the rejection of novel foods are emotions of disgust and fear, intensified by food neophobia and cultural norms. Consumers are more likely to think ingesting nanomaterials in food is riskier than, say, having them in food packaging (Monaco *et al.*, 2024). Scientists, however, emphasise health risks from nanoparticles moving from nanopackaging to food. Researchers found that nanoparticles like silver, titanium dioxide and zinc oxide can migrate under certain conditions, resulting in potential human exposure and related health risks (Gupta, Guha and Srivastav, 2024). This means that nanoparticles can cause damage to the cells due to oxidative stress, inflammation and cellular malfunction.

Ahmad et. al. (2023) identified extra risks related to nano-based food packaging. Studies show that nanomaterials may cause cytotoxicity and migration behaviours, which raises consumer concern over the ingestion of nanoparticles owing to migration from the packaging (Ahmad, Qurashi and Sheehan, 2023). These risks are important because they shape how people perceive based on exposure. In the same way, it is necessary to recognise consumer concerns about the migration and toxicity of nanotechnology in food packaging. Regulators must ensure thoroughness when it comes to the migration and toxicity issue to instil public confidence, especially in the case of direct food contact (Alfei, Marengo and Zuccari, 2020). According to joint research by Dijkstra and Critchley, there has been public concern about nanotechnology. Participants from the Dutch science cafés have shown anxiety regarding the long-term environmental and safety effects of nanomaterials. Public attitudes towards nanotechnology are shaped by their view of the risks of wanting unintended consequences, is further leads to concern for consumer attitudes towards acceptance (Dijkstra and Critchley, 2016). Consumer views regarding the risks of nanomaterials are influenced by emotional factors, migration concerns, health effects and environmental damage. Clear and transparent communication that addresses these worries is essential for consumer adoption of nanotechnology in food.

4.1 Scientific Literature on Risk Assessment

The international scientific literature on the risk assessment of nanomaterials in food indicates that although safety assessments are required, there are gaps in the assessment. Risk assessments from regulators determine the public trust and acceptability of new food technologies. Assessments from regulatory bodies also greatly influence perceptions about nanomaterials in food packaging. Safety assessments generally evaluate whether nanoparticles from packaging will migrate into food and from food into the human body. Studies on migration are important as they can estimate the likelihood of exposure to nanomaterials. They provide data to assess safety standards and consumer protection measures. Because of differences in the types of nanomaterial, their behaviour and their probable health effects, regulatory agencies have difficulty coming up with complete evaluation procedures (Wyser *et al.*, 2016). That's why international guidelines must be harmonised to address regulatory discrepancies and bolster consumer confidence.

In addition, Kaur et al. (2024) thoroughly evaluated the toxicological impact and gastrointestinal behaviour of nanoemulsions in foods. Nanoemulsions can be used to enhance food products by improving their bioavailability of nutrients, flavour and antimicrobial properties. However, since these properties are at the nanoscale, they may result in toxicology and bioaccumulation or interaction with biological systems. There is a need for extensive toxicological evaluation and advanced analytical methods to accurately assess the safety of nanoemulsions. Evaluations of such nanoemulsions help the consumer in offering transparency regarding a cause-and-effect association (Kaur *et al.*, 2024). Scientific risk assessments of nanomaterials must be thorough, transparent and communicated to consumers to gain consumer acceptance. Regulatory frameworks and scientific evaluations should be regularly updated as new developments occur with nanotechnology to enact safety protocols when required.

4.2 Impact of Risk Communication on Consumer Acceptance

Consumers are more likely to accept nanomaterials in food when effective risk communication takes place. Through effective and targeted communication, concerns can be responded to, public trust can be built up, and thus consumers can accept novel food technologies. Chinese food safety risk communications strategies can be effective through the system dynamics model. A study by Liang (2021), indicates that effective two-way communication significantly increases consumer trust and acceptance of food safety. Involving different groups like food businesses, regulatory officials, scientific experts, media practitioners, and the public in open dialogue may go a long way in improving public confidence and reducing risk perception (Liang, 2021). Moreover, research indicates that the transparency of the regulator and the clarity of communication are important. Another study conducted by Chelladurai et. al (2019), communicates that the regulatory frameworks and assurance of safety affect consumer trust in nanotechnology applications (Chelladurai and Jayas, 2019). When regulators transparently share their procedures and safety assessments, it reassures consumers and paves the way for enhanced acceptance of nanotechnology in food.

A survey of consumers in the U.S. shows how subjective norms, institutional trust, and perceived benefits influence consumers' attitudes towards nano foods. According to the regression analysis, effective use of labelling, awareness campaigns, and social influence is likely to enhance acceptance levels by stressing the consumer advantage and reducing perceived risk (Parrella *et al.*, 2024). A table in the article by Parrella et. al. (2024) is visually recreated below. It shows a regression model highlighting the influence of perceived benefits, subjective norms and institutional trust. As Figure 5 depicts, being clear on benefits and communicating thoughts and ideas openly and transparently helps with the acceptance of nanotechnology in food.

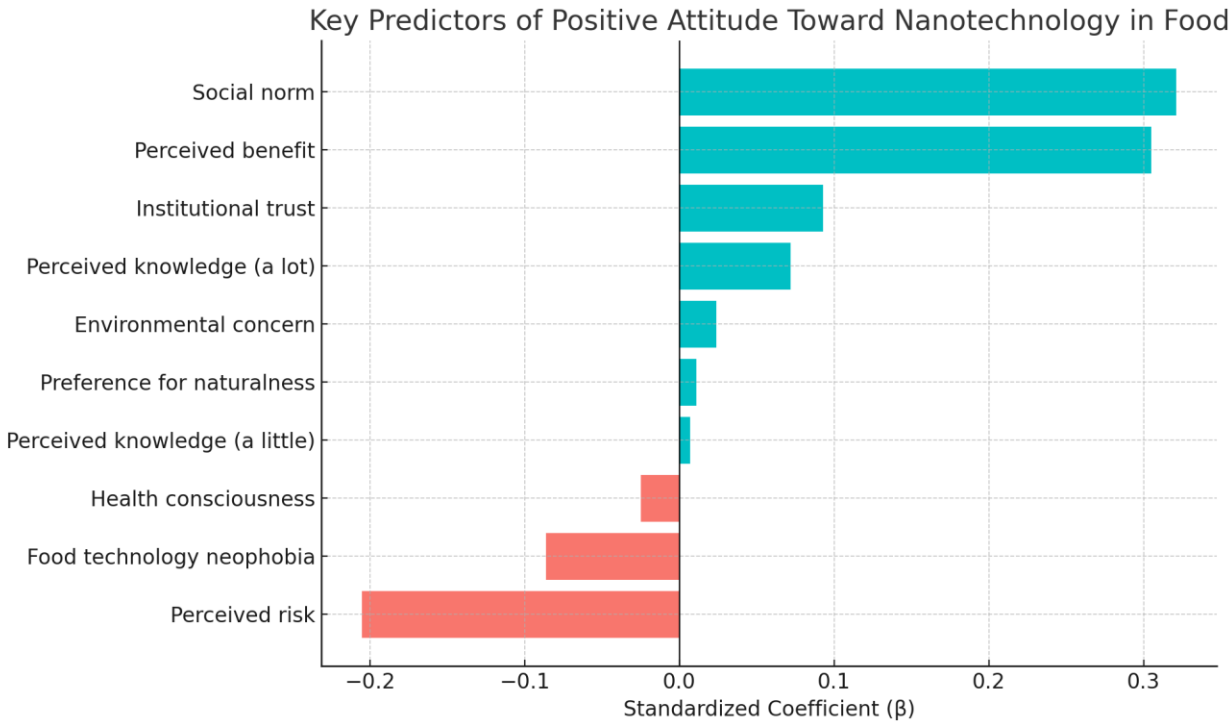

Figure 5: Key Predictors of Positive Attitude Toward Nanotechnology in Food (Parrella et al.*, 2024)*

The above chart outlines the message to boost interest in the benefits as well as help maintain a trusted and transparent public perception. Support from society or peers is the strongest positive predictor of acceptance of nanotechnology. When consumers perceive that nanotechnology offers benefits, they will accept it more easily. The acceptance of nanotechnology is positively influenced by trust in government, industry and research institutions. On the contrary, increased intolerance toward risk impacts negative acceptance and fear or aversion toward new food tech, reducing acceptance. Having transparent risk communication, sending out clear messages about the benefits and engaging with stakeholders are key to consumer acceptance of nano-enhanced products in food. The study shows that more systematic risk communication is required. The risk communications tactics can help tackle the public's apprehension about risks regarding food tech and help consumers accept the novel food tech.

5. Comparative Analysis of Consumer Perception vs. Risk Potential

It is important to know how consumer perception differs from scientifically grounded risk assessment to improve public acceptance and increase effective risk management. Novel food consumers perceive a risk that diverges substantially from the scientific risk assessment; this situation is grounded in cognitive biases and heuristics. Emotions of disgust and fear play very important roles in triggering various heuristics, like the "natural is better". These heuristics distort consumer judgements of real risk. Consumers' perception of novel foods, including nanofoods, is influenced more by emotions than by facts. As a result, consumers will most likely perceive them as unsafe, despite risk assessment performed by scientists showing no concerning risk (Monaco *et al.*, 2024). There is a huge gap due to food neophobia, so clear communication is needed.

Van Dijk et al. (2017) offer further insights through their analysis of stakeholders' attitudes towards nanotechnology across various sectors, including food. Their study shows there are many differences between what stakeholders think and what scientists assess. This happens due to a lack of psychological understanding or information. Stakeholders largely have a higher risk perception for nano-food applications than for those in water, energy, and medicine because the latter are perceived as having a lower need for urgency and, as a result, greater uncertainty around exposure and risk. Stakeholders expressed concerns about unknown long-term effects and exposure pathways, which are less clear for nano-food applications than for medical or environmental applications (van Dijk *et al.*, 2017).

According to Wyser et al. (2016), there are evident differences between consumers' concerns and scientific risk data regarding the use of nanotechnologies in food packaging. Many people worry about nanoparticles in food packaging and their possible harmful effects. Research conducted reveals that consumer exposure through nanomaterial migration is limited or negligible (Wyser *et al.*, 2016). Though there exists rigorous research, nonetheless, uncertainty and complexity regarding regulatory approval processes and life-cycle safety assessment of nano-enabled packaging continue to raise consumer concern and the perception-risk gap. Public risk perceptions of nanotechnology applications in food are influenced by cognitive heuristics, emotional responses, and informational gaps, which show drastic differences with scientific data. Bridging these gaps calls for communication strategies that adequately and effectively convey the scientific evidence to the public.

5.2 Cross-Industry Comparisons

A cross-industry examination allows us to identify why attitudes to nanotechnology differ in sectors. Comparing the risk perception and acceptance of nanomaterials in food and other products suggests the following: Consumers differentiate nanotechnology applications based on usefulness, need, and associated risk. Because the benefits are clear and the need is apparent, this application receives the most consumer acceptance. Compared to pharmaceuticals, food nanotechnology applications have greater consumer anxiety due to fears over nanoparticles (Gupta, Fischer and Frewer, 2015).

Gupta et al., 2015 provide a graphic illustration of comparative acceptance across sectors, which clearly shows these sectoral differences. The study found that consumers' attitudes are shaped by feelings of invasiveness and exposure to the body (Gupta, Fischer and Frewer, 2015). The representation in Figure 6 shows how different applications of nanotechnology are perceived based on their usefulness to individuals and their necessity to society. Nanotechnology applications like targeted drug delivery, water filtration and brain implants appear in the right-top quadrant, indicating consumers view them as highly necessary and personally beneficial. Applications related to food, including food packaging and the encapsulation and delivery of nutrients, receive similarly high marks, indicating broad public appeal as they are easy to understand and relevant. Technologies such as RFID tags, nano fabrics and smart dust for military applications cluster in the lower-left quadrant, indicating that consumers identify them as lacking need and having low personal relevance. The results indicate that consumers' acceptance of nanotechnology will depend on the perceived functional value and need for or relevance of applications. Food and health-related applications score the highest.

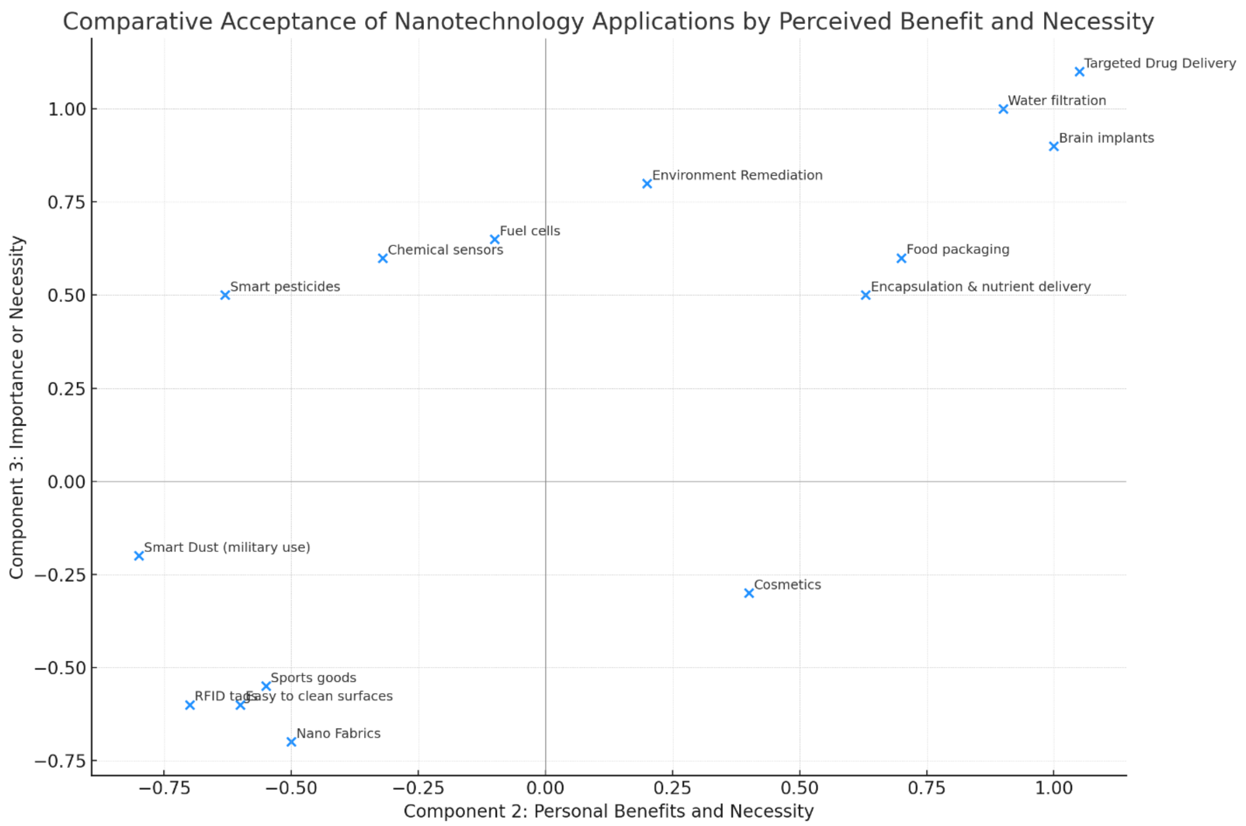

Figure 6: Comparative Acceptance of Nanotechnology Applications by Perceived Benefit and Necessity (Gupta, Fischer and Frewer, 2015)

Handford et al. (2015) find support for this conclusion, showing that consumer attitudes in the agri-food sector differ significantly from those in other sectors. Most people have a positive feeling about nanotechnology applications for packaging, food safety monitoring, and agriculture because of their perceived direct benefits to consumers for safety and shelf-life. Nonetheless, regarding direct food applications involving either nutritional enhancements or ingredient alterations, consumers' attitudes are rather negative, which is closely related to how they perceive it to be intrusive (Handford *et al.*, 2015). This distinction highlights the importance of perceived nearness and control, with consumers being more favourably disposed to nanotechnology that increases safety outside the food, rather than a structural alteration of the food itself.

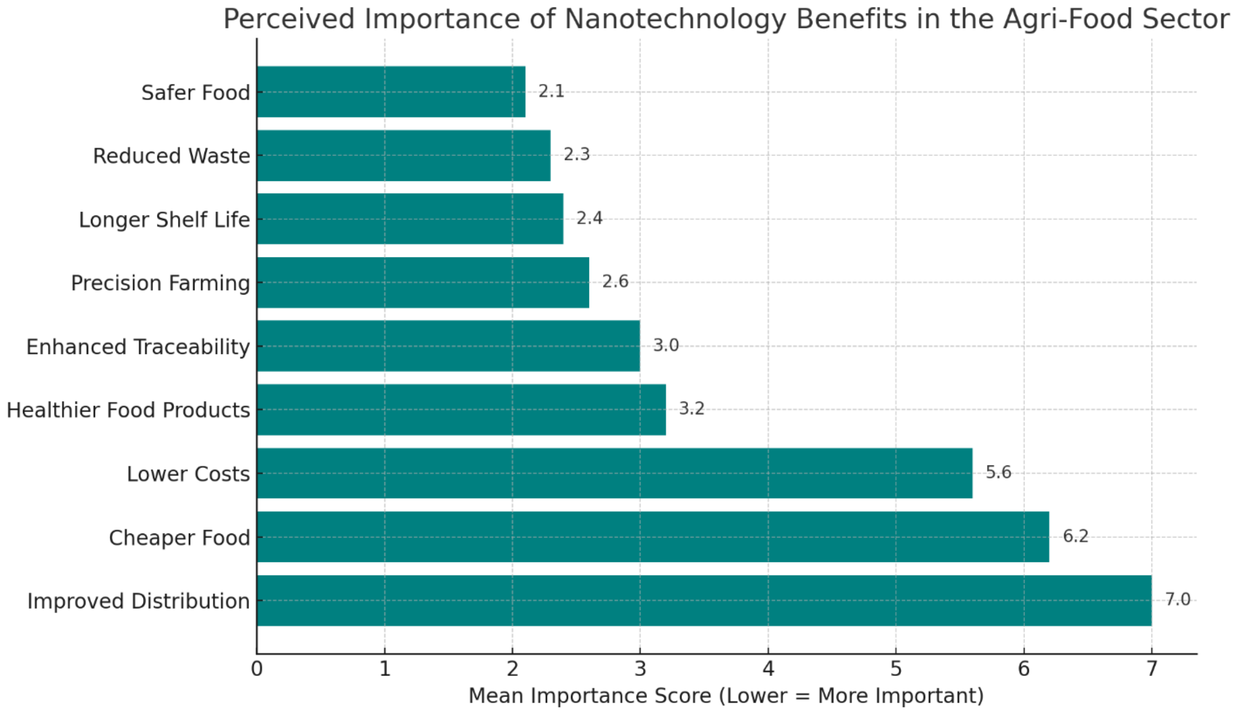

Figure 7: Perceived Importance of Nanotechnology Benefits in the Agri-Food Sector (Handford et al.*, 2015)*

Based on the mean score, where higher values indicate lower importance (as shown in Figure 7), the nanotechnology in agri-food smartness is a horizontal bar chart on the importance of various potential benefits of nanotechnology. According to the results, the most important benefits of adopting nanotechnology include safer food (with a mean score of 2.1), reduced waste (2.3), and longer shelf life (2.4). The most valued benefits highlight the focus of the sector on making food safer and better. On the other hand, they ranked cheaper food (6.2) and improved distribution (7.0) as less important benefits, signalling that stakeholders are focused more on intrinsic food quality and public health outcomes than cost-related benefits. Statistics indicate that the future of nanotechnology in food systems will rest on its potential to mitigate key safety and sustainability challenges, rather than lower production costs.

These findings highlight the need for tailored risk communication. Communication that is clear and transparent can address consumer apprehensions specific to each sector, enabling a greater understanding of and acceptance of nanotechnologies. Communication should stress clear benefits to consumers as well as clarify safety practices and uncertainties that consumers see with the direct consumption of nano-enabled foods.

5.3 Cultural and Regional Differences in Perception

Age, education, and location are demographic factors influencing consumer views on food nanotechnology. Some researchers mention that the younger generation of consumers is more open to technological innovation, like nanotechnology. Researchers Jeong and Lee (2021) note that the younger generation had a greater willingness to accept nanotechnology in food if communicated benefits were used (Jeong and Lee, 2021).

Cultural and regional contexts significantly shape consumer perceptions of the risks and benefits of nanotechnology in food use. According to Dijkstra and Critchley (2016), findings from Dutch science cafés suggest that Dutch people have positive attitudes toward nanotechnology and that science café visitors voiced significantly fewer concerns than the public. After these discussions, the participants showed a degree of awareness of risks; however, the benefits were highlighted more (Dijkstra and Critchley, 2016). The grouped bar chart compares the most important predictors for positive attitudes toward nanotechnology by two types of engagement, namely, surveying participants directly from Science Café and a Digital Group (digitally surveyed). Across both groups, positive applications appear to be a key driver, with a notably stronger effect observed in the digital group (β = 0.38) than in the Science Café group (β = 0.22). In the same vein, the intention to search for information and talk to others has all recorded positive contributions for both groups. However, they have all been found to be more influential for the digital group. Notably, risk applications exhibit a small negative impact in Science Cafés (β = -0.01), whereas digital users exhibit a much greater negative effect (β = -0.19), indicating that this group is more sensitive towards the risk. As depicted in this figure, while both groups consider information-seeking and perceived benefits to be important, digital respondents tend to be more polarised, reacting more strongly to the promise and the risk of nanotechnology.

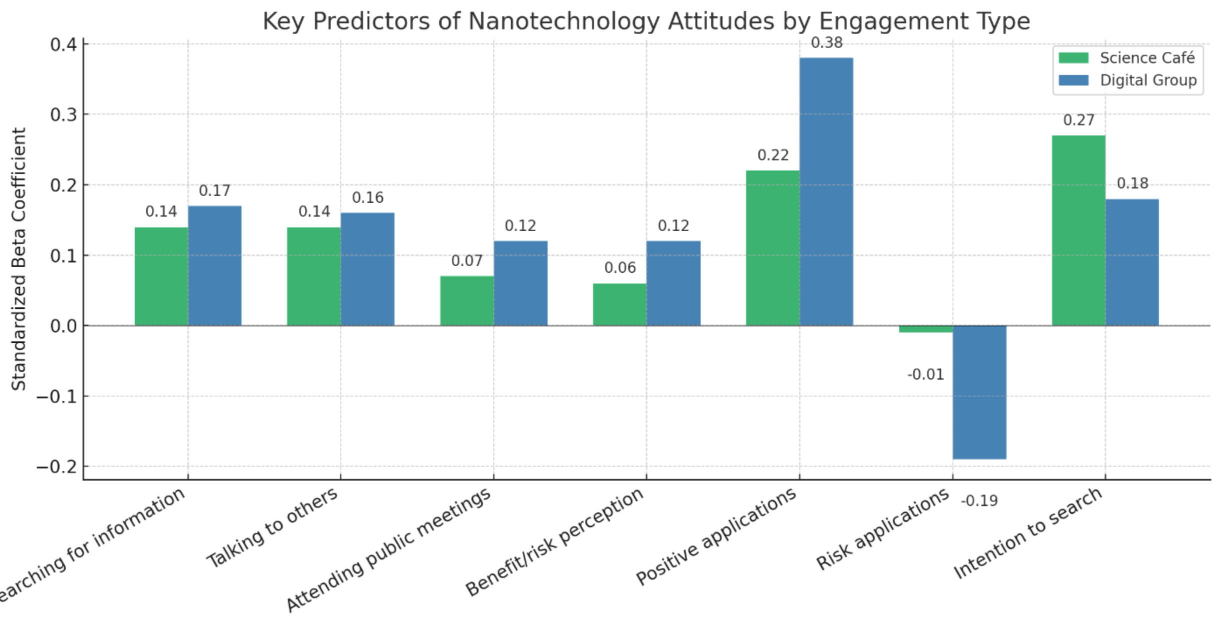

Figure 8: Key Predictors of Nanotechnology Attitudes by Engagement Type (Dijkstra and Critchley, 2016)

Parrella et. al. (2024) show in their study that consumers in the United States have neutral to slightly cautious attitudes towards nanotechnology. Moreover, they are mostly affected by perceived benefits, subjective norms, and institutional trust. Their survey highlights that subjective knowledge, social norms, and institutional credibility have a strong impact on consumers' attitudes, suggesting a more individualistic and trust-based framework than Europeans (Parrella *et al.*, 2024). Cross-cultural studies have shown significant differences between Western and non-Western contexts. The people in Saudi Arabia very significant influence on consumer attitudes towards food safety. These included nanotechnology applications with the help of cultures and religion. The acceptance and sceptical attitudes of consumers in different regions are defined by such culturally embedded factors (Almaghrabi, 2023). The findings, which seem to show diverse preferences and attitudes, therefore underline communication challenges, revealing that cultural attitudes, regional behaviour, and societal trust are paramount for effective oversight of public opinion towards the global acceptance of nanotechnologies.

6. Regulatory and Ethical Considerations

It is important to understand the relevant regulatory frameworks applicable to nanomaterials in food. These structures can greatly influence consumer perception and trust, and the market introduction of new nano-enabled products. There has been reduced public opposition to new food technologies through appropriate public regulation, consumer education measures, and tweaks in marketing methods. Countries that have applied obligatory labelling laws and transparency actions, for example, the EU, have seen constant opposition, but also enhanced consumer autonomy and reliance on regulatory bodies in the case of GMOs. (Ichim, 2021). In contrast, in regions where GMO labelling is not mandatory, such as the U.S., consumer acceptance has been high, but some critics attribute this to a lack of transparency, not public trust

The public's view has also changed due to consumer awareness and knowledge. In areas where authorities and industry have run public education campaigns promoting the safety and advantages of new food technology, consumer mistrust has been steadily eroding. For instance, educational initiatives around food irradiation in the U.S. have decreased fears after making clear that these technologies are safe (Natividade, Alonso and Mesquita, 2023).

Consumer perceptions have been influenced by marketing that emphasises benefits like greater shelf life, less food waste, and enhanced food safety. Nonetheless, these techniques need to be paired with transparency and concise communication about possible risks to avoid further eroding public trust. The demand for natural ingredients helped in a clean label movement in Europe, where huge disapproval took place against synthetic additives and preservatives, but still promoted the advantages of modern food preservation techniques (Hasmin *et al.*, 2020). These initiatives provide security for the public and help increase their acceptance level regarding nanofood.

6.1 Overview of Current Regulatory Frameworks

International rules are meeting consumer demand for transparency, particularly in the labelling and safety assessment of food nanomaterials. Regulation EU 1169/2011 makes food producers label any food that has engineered nanomaterials (ENM) as "nano" before the ingredient to indicate the presence. The goal of the labelling is to improve consumer transparency and trust by clearly indicating the presence of nanomaterials in the food product. Nonetheless, it is challenging to harmonise labelling requirements internationally. Regulatory definitions of ENMs, analytical detection methods, and international labelling standards differ, which can create important trade barriers and consumer confusion (Grieger *et al.*, 2016). Coordination on the international level is essential for effective risk communication and consumer protection.

Different regions have different rules when it comes to food packaging and direct food application. European Union Regulation 10/2011 sets out stringent requirements for plastic food contact materials, which include authorisation for the use of nanoparticles. Some nanoparticles, like silicon dioxide and titanium nitride, are approved for use; others are not on the list. It makes it difficult for the industry to comply and communicate with consumers (Wyser *et al.*, 2016). Swiss regulations are like those of the EU but with some nuances. Switzerland makes it obligatory to label food if it contains synthetic nanomaterials, which is in line with the EU. This action aims to improve public confidence in the regulators and the industry. The public's perception and acceptance of nanoparticles in Switzerland depend on clear communication of the potential risks and benefits from regulatory authorities. This shows that effective legislation and clear guidelines can influence consumers' confidence (Rothen-Rutishauser *et al.*, 2021). Conversely, the U.S. FDA has not yet mandated specific labels for nanomaterials, but instead, deals with individual nanotechnology products on a case-by-case basis. The FDA states that new nano-enabled products may call for additional safety evaluations and scrutinise, although it does not have guidelines for nanoparticle size, safety and labelling (Grieger *et al.*, 2016). The lack of regulatory certainty creates confusion for American consumers and hinders their confidence in nano-enabled products as compared to Europeans.

To achieve consumer trust, regulations must keep pace with the latest science on nanomaterial safety. Better risk assessments, clearer definitions, and standard global regulatory frameworks are needed. These developments should enable the regulatory environment to contain potential risks, clarify public perception and encourage consumer acceptance of beneficial food applications of nanotechnology.

6.2 Industry Transparency and Ethical Responsibility

The introduction of nanomaterials in food produces ethical issues regarding transparency, the safety of consumers, as well as the consent of the consumers. For instance, there seem to be few to no provisions that require clear indications on the foods that contain nanomaterials. With the currently available guidelines, information on food products with altered nanoscale properties may be hidden from consumers, thus making them consume such foods without their knowledge (Hasmin *et al.*, 2021). Such an openness to deficiency is risky to build consumer confidence and especially raises the issue of consumer rights to information on what they eat.

A few representatives had made a case dictating that equity in nanotechnology regarding the food industry is paramount and disturbing. Some coefficients and characteristics of the development and implementation of nanomaterials may be acquired by large and potent companies, leaving behind small-scale producers. This might necessarily create a monopolistic environment in the food processing and distribution industry, wherein a few companies with extant advanced nanotechnology would constrict the market (Kuang *et al.*, 2020). These asymmetries might aggravate already existing disparities in food production and distribution, growing moral concerns about the fairness of the perceived benefits and risks of nanotechnology.

The ethical argument also relates to the possibility of health-related issues that would arise in the future, as well as the environmental risks associated with the nanomaterials. When properly applied, modern nanotechnology could offer ways of preventing or minimising some of the negative impacts faced in food production, but still, there are serious issues that scientists have not interrogated in terms of the use of nanotechnology. The danger of the consequences is illustrated in the case of nanomaterials finding their way into the body or the environment, and anxiety calls for the responsible usage of technology (Siddiqui *et al.*, 2022). The ethical aspects must include the precautionary principle, which means that it should be ensured that the use of nanotechnology does not endanger public health or the environment.

6.2.1 Role of Transparency and Labelling in Mitigating Concerns

Clear labelling significantly enhances consumer confidence. When products are clearly labelled, consumers can feel confident about what they're buying. The question of whether consumers should have the right to make informed choices about their food is also answered by this regulation. Labels should enable consumers to understand the food's content, how it was produced and where it comes from (Grieger *et al.*, 2016). Yet, clear labelling may create bad consequences. People don't know what nano means, so they generally think badly of it. Consumer perceptions can change when they see labels that refer to the presence of nanomaterials as warnings of a higher risk (Grieger *et al.*, 2016). So, putting labels on products can sometimes create problems for consumers in understanding products.

Studies indicate consumer reactions to labelling vary greatly depending on knowledge, perception of risk and cultural background. Studies of consumer attitudes toward nanotechnology have shown that when food products are labelled as "Nanos", knowledgeable consumers show a greater level of trust, but the less informed group develop greater scepticism (Chang and Chen, 2022). As such, labelling should consider the knowledge and perception of consumers. When food is safely available, better labelling also promotes trust between consumers, food safety authorities and manufacturers. Universal labels are the answer; ISO aims the improve transparency in all industries regarding nanomaterials (Grieger *et al.*, 2016). Nevertheless, labelling must not burden the consumer with excessive detail as this would lead to confusion, which is counterproductive.

Labelling ultimately helps to create harmony between the innovative development of food technologies and consumer acceptance. Regulators and food industries must proactively make consumers aware of the benefits and risks of nanomaterials. Uniform international labelling regulations can further ease consumer apprehensions, avert misunderstandings, and ensure knowledgeable and assured consumer preferences (Grieger *et al.*, 2016). Careful labelling strategies that come with educational initiatives can help innovation and technological advances be understood and widely accepted by consumers.

6.2.2 Challenges in Implementing Nanomaterial Labelling

There are practical and regulatory challenges that hinder the implementation of nanomaterial labelling in food. One of the main difficulties is the lack of current internationally accepted definitions of nanomaterials, which hinders regulatory uniformity and enforcement across borders. The European Food Safety Authority (EFSA) points out that categorising the materials is not easy because they can differ not only by size and composition but also by how they interact with biological systems (Grieger *et al.*, 2016). As a result, a lack of clarity creates uncertainty internationally, which in turn leads to confusion and reluctance in consumers.

Another issue involves difficulty in measuring the number of specific nanomaterials in food. Traditional analytical methods often fail to accurately detect and quantify the presence of nanomaterials in food. Researchers say there's difficulty in detecting engineered nanomaterials (ENMs) of various substances in a range of food matrices because standard analytical techniques are limited and expensive. Experts say that better analytical methods are required to guarantee effective labelling and consumer trust (Grieger *et al.*, 2016). If people don't trust the testing, they might find it difficult to trust the package labels.

To solve these questions about labelling coordinated global regulatory efforts, standardised definitions and, most importantly, advanced analytical techniques are required. Having clear guidelines and stronger analytical tools for labelling will increase transparency, help alleviate public concern and build consumer confidence.

6.2.3 The Future of Nanomaterial Labelling in Food

The future of food labelling using nanomaterials depends largely on international cooperation, technological developments and consumer communication. Experts say that the development and consensus around shared definitions, standards and detection methods at the global level will ensure consistency across regions (Grieger *et al.*, 2016). This kind of standardisation would greatly reduce confusion and enhance consumer acceptance worldwide.
Anticipated technical advances in detection and analysis will be applied to nanomaterials for labelling in the future. New tools, like better detection methods, will make it easier to confirm the accuracy of nanomaterial labelling. Recent advancements have led to clearer labelling, which may alleviate consumer fears with scientific evidence on nanomaterial safety (Chang and Chen, 2022). Detection methods will continue evolving, thus labelling transparency and consumer confidence will also keep improving.

The success of nanotechnology in food products will depend on effective consumer communication. For shaping positive perceptions and reducing scepticism, it will be important to provide consumers with transparent, consistent, and easily understandable information about the benefits and risks of nanotechnology. Regulators, industry leaders, and scientists must get together in advance to help consumers understand and clearly state both the benefits and safety issues of nanomaterials in food products. Clear labelling and effective communication will be essential for aligning technology development with consumer acceptance of nanoenhanced food products.

6.2.4 Obligation of Corporate Social Responsibility (CSR) in Influencing Consumer Attitudes

Corporate social responsibility significantly influences consumer attitudes towards food that is manufactured using novel technologies such as nanomaterials. When companies are clear about what they do, it creates a positive attitude among consumers regarding their products and services. Having a strong and transparent CSR strategy can enhance consumer trust in the company. Handford et al (2015) discuss that if an organisation openly conveys its CSR commitment regarding food safety, it can establish consumer trust and acceptance of new technologies in food products. On the other hand, a lack of transparency in CSR activities could increase the level of consumer scepticism, leading to public distrust, hampering consumer acceptance of new technologies (Handford *et al.*, 2015). Consumers are demanding that food companies act and proactively address their concerns through visible CSR. Transparency in CSR activities has the opposite effect of heightening scepticism and generating mistrust in the public's mind, making it hard for consumers to accept new technology. If a company uses labels and delivers a clear CSR message, it is seen as a responsible and reliable firm.

Handford et al. (2015) mention that clear, consistent and open research activities respond effectively to consumers' scepticism towards new agri-food technologies. Such transparency helps to inform consumers and engages them in this innovation by alleviating their fear of the unknown risks associated with all food innovations, including those involving nanomaterials (Handford *et al.*, 2015). As a result, companies with more transparent CSR initiatives and open communication should garner better acceptance of nano food products.

Effective communication measures the conversion of CSR initiatives into consumer acceptance. When the facts are clear and not too complicated, they remove the public confusion and scepticism about food safety. Better communication strategies help lessen the knowledge gap between consumers and food producers, thus improving consumers' perception and acceptance (Handford *et al.*, 2015). When CSR initiatives communicate proactively and transparently, people recognise that food technologies can be safely used and accepted. Communicating the benefits and risks of nanomaterials in food helps the consumer to make an informed choice. When the CSR practices and labelling aren't clear or well communicated, confusion arises, which leads to an increase in scepticism and rejection of nano-enabled food. Thus, corporations that are transparent, honest and clear in their communication can manage consumer expectations effectively and build sustainable relationships based on trust and credibility.

7. Gaps in Literature and Future Research Directions

There are still many research gaps in the food industry about nanotechnology. Much of the existing literature focuses on the short-term study and theoretical aspects, while long-term consumer behaviour and regional differences are few in between. Data from non-Western countries is missing. Examining them as their regulations and cultures differ could provide great new insights. Moreover, little reference has been made to the long-term effects of risk communication strategies as well as how public trust changes over time.

Another gap exists between consumer perception and the actual purchase behaviour of consumers. Though surveys frequently measure acceptance, their application in the marketplace remains largely unstudied. Moreover, it is uncommon for literature to conduct comparisons of the acceptability of nanotechnology in sectors such as food, cosmetics and medicine, which could help understand trust and perceived safety.

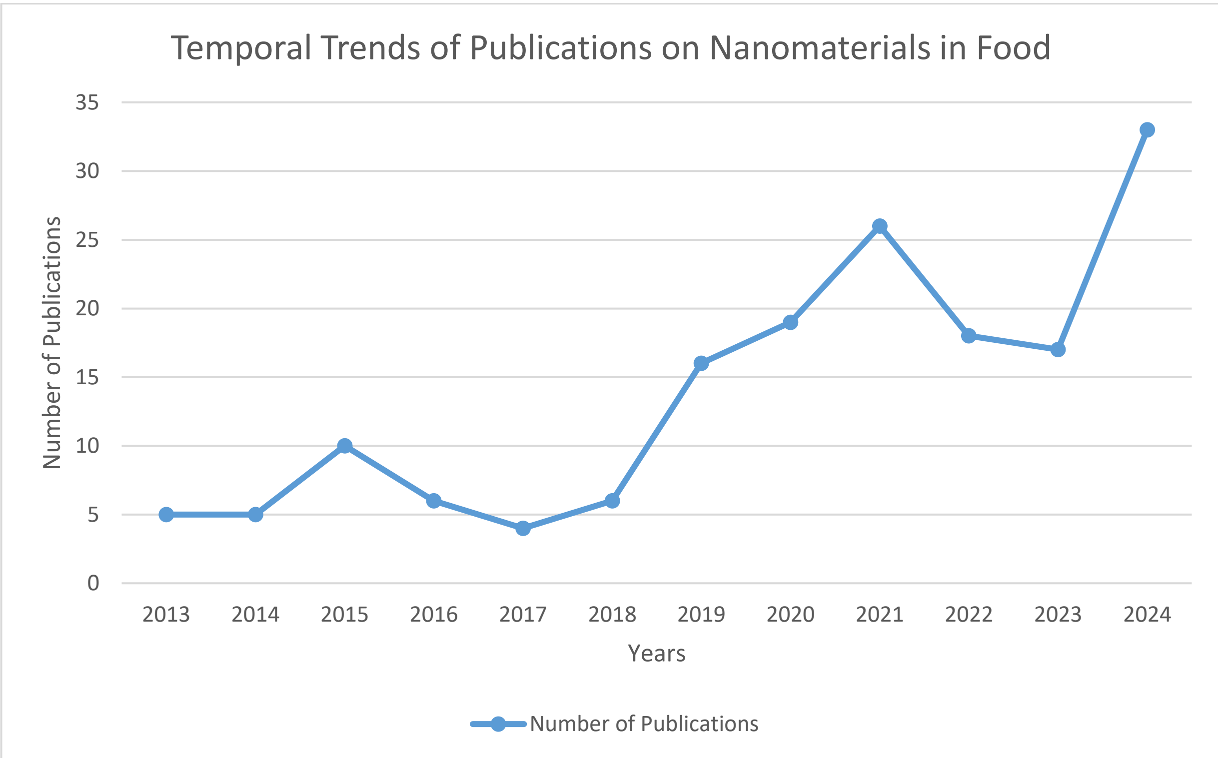

Figure 9: Temporal Trends of Publications on Nanomaterials in Food

Figure 9 shows the yearly publication statistics. Research on nanomaterials in food grew steadily from 2013 to 2018. The number of publications remained low, from 4 to 10 per year. In 2019, research activity increased sharply. In 2021, more than 25 publications were made, showing increased interest by scientists and regulators. Between 2022 and 2023, the number of studies slightly decreased but stabilised at around 18–20 per year. In 2024, there was a large jump in publications to 33. This spike indicates technology advancements in the field and regulators like EFSA publishing their works. Overall, research on nanotechnology in food is still increasing. The initial years show slow progress. The first peak year occurs during a year of major regulatory discussions. Based on the trends for recent years, it is expected that there will be an inclination for applied research. Further, there are expected breakthroughs in the year 2025.

7.1 Identified Gaps in Consumer Perception Research

Consumer perceptions of nanomaterials in food applications are important. However, there are clear gaps in the existing research, particularly on long-term consumer behaviour and data from under-researched areas. Much of the literature provides short-term and lab studies, not long-term consumer data at all. Bandala and Berli (2019) highlight that the long-term impact of engineered nanomaterials (ENMs) on the environment and human health is highly uncertain. The potential for long-lived engineered nanomaterials (ENMs) to cause health-related and other problems, particularly through contamination of various levels of environmental media and food and feed, is uncertain (Bandala and Berli, 2019). The unavailability of long-term data makes understanding the consumer risk perception and health impact in long-term situations difficult.

The emotional aspects influencing consumer acceptance are another important data missing. Feelings of disgust influence consumers' perceptions of risk. Studies show that food disgust sensitivity is an important factor that affects risk-benefit and acceptance. Although we know that disgust is an important emotion that interacts with other feelings, such as curiosity, the current literature has not yet investigated how these feelings may evolve and/or change with successive exposures and/or familiarity with nanofood products (Egolf, Hartmann and Siegrist, 2019). Researchers haven't studied differences in belief systems and cultures across regions. The authors Gupta et. al. (2024) admit to very large culture and region-related differences in consumer perceptions, especially in Western and non-Western contexts. Cultural norms, religious beliefs, and trust in regulatory institutions can greatly influence how people perceive nanotechnology (Gupta *et al.*, 2024). Nonetheless, there is a lack of strong empirical data from the non-Western and developing world explaining the applicability of the perception and risk communication model.

The use of different nanomaterials, especially natural polymers, points further to gaps in understanding. Sampathkumar, Tan, and Loo (2020) explain how nature-derived polymers can be useful for nano-delivery systems in food and agriculture, giving the following results. Even if these materials are marketed as safer and more sustainable options, there are very few studies that look at consumer perceptions of these nano-delivery systems. The absence of studies renders it difficult to ascertain whether consumers make a distinction between synthetic and natural nanomaterials about perceived risks and benefits (Sampathkumar, Tan and Loo, 2020). It will be essential to address the gaps indicated through extensive longitudinal studies, including different cultures, and examining natural and synthetic nanomaterials. Filling these gaps would provide a more accurate understanding of consumer behaviours and thus greatly assist in the responsible use of nanotechnologies in food production and packaging.

7.2 Areas Requiring Further Research

Consumer perceptions of nanomaterials in food are a comparatively under-researched area. This makes clearer definitions of important terms necessary. More long-term studies, consumer perception of natural versus synthetic nanomaterials, cross-regional comparisons, and risk communication strategies are required. To effectively assess the evolution of consumer perceptions, longitudinal studies remain important. Personal feelings like disgust affect many consumer decisions. Egolf et.al (2019) mention that not knowing how emotions and perceptions change when consumers are exposed to nanofoods for a long time is another field worth exploring (Egolf, Hartmann and Siegrist, 2019). Future research should examine consumer attitudes over time to see how experience and exposure to nanofoods alter their perceptions and acceptance.

One more major gap that also needs to be filled is cross-regional comparative analysis research. Research shows big differences in how consumers think of things based on demographic differences (Europe versus the USA) (Dijkstra and Critchley, 2016), (Parrella *et al.*, 2024). More empirical studies in non-Western contexts, as recommended by Gupta et al. (2015), can make it possible to further global insight (Gupta, Fischer and Frewer, 2015).

Consumer perceptions of natural and synthetic nanomaterials need more attention. According to Sampathkumar, Tan and Loo (2020), there is an increase in the usage of polymers from nature, which consumers might deem to be inherently safer. It would be beneficial to conduct full-fledged studies to compare consumer acceptance of natural versus synthetic nano-delivery systems, as they differ in preferences and safety perceptions. The full lifecycle impacts (LCAs) of nanomaterials should be established from synthesis to disposal (Gupta, Fischer and Frewer, 2015). Different studies raised concerns related to the migration of nanoparticles and the environmental impact of food packaging. Future studies ought to consider undertaking detailed life cycle assessments that provide thorough evaluations.

Figure 10 shows how nanoparticles can get into the food. The maximum migrated amount of each nanomaterial at the x-axis is a unit of measurement that varies from single digit nanograms per kilogram (ng/kg) to milligrams per square decimetre (mg/dm^2) to milligrams per square centimetre (mg/cm^2) to single digit micrograms per litre (µg/L) etc. depending on the study. Zinc nanomaterials migrate much more than any other individual material, reaching up to 1766.60 µg/L. TiO_2 and ZnO, as well as zinc oxide, also showed relatively high migration (e.g. 52.74 ppm and 18.70 mg/dm^2).

TiO_2 and ZnO, as well as zinc oxide, also exhibit relatively high migration (e.g. 52.74 ppm and 18.70 mg/dm^2). Silver nanoparticles and silver show relatively low migration < 1.5 ng/kg and 0.141 mg/dm^2, respectively. Cellulose nanocrystals and magnesium oxide are below the normal level of 10 mg/dm^2. The bar chart helps to visualise the migration potential of different nanomaterials. Most of the nanomaterials studied have a migration lower than the safety limit. Only the nanomaterial zinc compounds need to be monitored closely. According to Gupta et al. (2024), this may aid in understanding the migration of nanomaterials and benefit regulation.

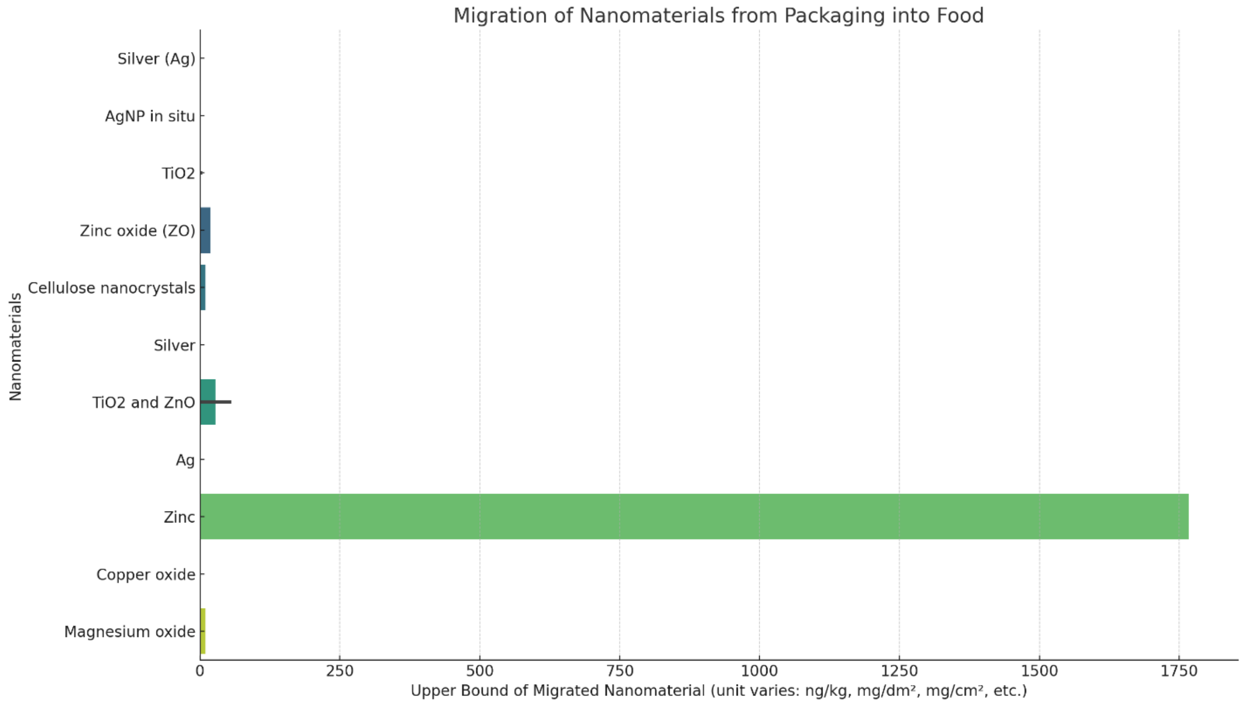

Figure 10: Migration of Nanomaterials from Packaging into Food (Gupta, Guha and Srivastav, 2024)

Finally, developing effective and targeted risk communication strategies is critical. Clear and transparent communication, effectively involving multiple stakeholders, is essential in building trust and acceptance of nanotechnologies (Liang, 2021). Future research should focus on understanding how best to communicate the benefits, safety, and uncertainties surrounding nanofoods. Research involving various stakeholders will increase consumer confidence and acceptance. By doing detailed studies and studies that compare two or more cultures at one time (Cross-Cultural Studies) for a long time (longitudinal studies) on the areas of research mentioned above and appropriate risk communication, consumer acceptance will improve and allow for proper inclusion of nanotechnology in the world food system.

7.3 Potential Future Trends in Nanotechnology Acceptance

It's important to understand how acceptance of nanotechnology will evolve for a successful future in the food and agriculture sectors. Advancements in technology combined with improved risk communication will influence these trends. As nanotechnology advances, consumers are likely to accept these products more as they are better explained and deemed safe and useful. Consumer confidence is enhanced through transparent communication that is evidence-based and highlights the safety and benefits (Gupta *et al.*, 2024). As nanomaterials advance and prove to be safer and more eco-friendly, particularly because of the greater use of natural biopolymers, consumer adoption is likely to rise in tandem (Sampathkumar, Tan and Loo, 2020). Moving ahead, consumer acceptance will depend on continued innovation plus clear, trustworthy communication that synchronises technological developments with public values and expectations.

Growth in consumer acceptance can be attributed to better and targeted risk communication strategies. The public can be influenced greatly if food safety communication is clear, authentic and made through the involvement of numerous stakeholders (Liang, 2021). As communication strategies change, with a focus on engaging with the public and open decision-making processes, consumers are likely to have a more positive view of nanotechnology. The future acceptance trends will be significantly influenced by cultural factors. Consumers' evaluations of risks are greatly influenced by culture. Future communication strategies may become more culturally sensitive in response to growing global interconnections and awareness of regional factors. This note indicates that regional values and beliefs will increasingly have a more pronounced impact (Dijkstra and Critchley, 2016; Parrella *et al.*, 2024). Due to this increased impact, communication that respects regional values will be important for building trust and accelerating global acceptance of nanotechnology in the food sector.

Further, it is expected that consumer exposure and education will increasingly familiarise society with applications of nanotechnology, hence reducing uncertainty and risk perception. Consumer acceptance in the first place is impacted by feelings, for instance, disgust. But, as people become used to nanofood and nanopackaging, negative feelings will likely diminish (Egolf, Hartmann and Siegrist, 2019). Bandala and Berli (2019) advise longitudinal studies in the future to collect much stronger evidence on how constant exposure positively changes consumer acceptance (Bandala and Berli, 2019). This indicates that repeated exposure and continuous education can gradually transform emotions and lead to the public's acceptance of nanotechnology in food systems.

Advancements in technology that were developed to tackle key consumer fears of migration of nanoparticles from packaging will enhance consumer confidence. By improving the barrier properties of food packaging, followed by advanced monitoring systems through nanotechnology, consumers will feel assured about food safety and environmental impact, thus increasing acceptance (Gupta, Fischer and Frewer, 2015). In general, consumers are likely to accept nanotechnology in food and agriculture over time. Advanced testing and monitoring systems, along with improved safety barriers based on nanotechnology, will ensure safety and environmental sustainability. We can expect that consumer acceptance of nanotechnology food and farms will steadily increase.

8. Discussion and Implications

This thesis looks at how consumers see and accept nanomaterials in the food industry, and their balance between perceived benefits and risks. As food is increasingly coupled with nanotechnologies, understanding consumer attitudes towards the same is imperative for stakeholders, policymakers, and researchers. The findings affirm some anticipated outcomes but also reveal unanticipated influences on consumer acceptance. They point out the complexity of consumer attitudes towards nanotechnology in food.

8.1 Findings

The research questions will be answered in sequence and order:

1. **How do consumers perceive and accept nanomaterials in the food industry compared to the potential risks associated with these materials?**

Consumers view the food industry’s nanomaterials as both dangerous and safe. Many consumers note the possible benefits, such as safe food, a longer life, and better nutrition. They appeared to be wary, nonetheless, due to health and environmental concerns. According to consumers, the risks that arise from unknown long-term health effects and unregulated use are too high for their benefit. According to them, studies claiming to prove that nano-food is safe for consumption have a limited duration and hence are not trusted. Scientific studies reveal the gap between science and public perception. We should look at other technologies and novel food uses that revolutionised the industry and learn from them.

2. **What factors influence consumer perceptions of nanomaterials in food?**

Consumers' perceptions of nanomaterials in food are affected by many factors, e.g. culture, awareness of technology, trust in food safety regulators, level of education, whether a person is resistant or open to new technology (neophobia), etc. Being cautious of technology can cause someone to refuse a product despite it being proven safe. A benefit is not enough for acceptance. Psychology and culture are deciding factors; thus, consumer perceptions are influenced by various demographic, psychological and cultural factors.

3. **How does risk communication impact consumer acceptance?**

Risk communication greatly improves consumer acceptance. When risks and benefits are communicated clearly, scepticism and fear are greatly minimised. Poor communication stirs up confusion and rejection. Media channels, especially, tend to exaggerate risks and have a bad influence on the mindset of consumers. The belief in communication enhancing acceptance was fulfilled. People have quite a lot of faith in regulators like the EFSA in Europe. With good communication tools, it could clear up a lot of consumer doubts. The results of the study aligned with the original assumptions, as it is evident that there needs to be trust and transparency in risk communication for novel food technologies to be accepted by society.

4. **How well do consumer perceptions align with actual risk assessments of nanomaterials in food?**

Consumers and scientists do not always agree on the same things. When consumers do not have much public knowledge of science or trust in the regulatory system, they may tend to overestimate the severity of the risks compared with what science indicates. Misinformation and incomplete information widen this gap. This difference is greater than expected, and more education and messaging about risk are needed. The results strongly back the assumptions about the surprisingly strong role of transparency, effective risk communication, and cultural sensitivity in the consumers’ acceptance of nanomaterials in food.

The public is split because it perceives the nanomaterials in the food sector as risky but also safe. Consumers recognise the possible benefits of food safety, a longer shelf life, and improved nutritional value, but are cautious due to health and environmental concerns. Consumers’ power to decide about the contents of what they consume daily, i.e. food and medicines, is being curtailed. People do not trust the food because, according to them, there are no long-term studies that prove nanoenhanced food is safe. Scientific knowledge and public perception show a gap; thus, consumers are more cautious than expected.

The belief that consumers find nanosensors (for pathogen detection or smart packaging) useful is proven true. The research reveals that consumer acceptance requires trust, transparency and perceived control. The promise of nanofood will only be accepted if the public is treated right. Consumers find it easier to accept passive use cases as they seem less intrusive. There is, however, research that shows that this feeling is not completely warranted, since there are particles like zinc that can migrate in relatively large quantities from the packaging into the food.

8.2 Theoretical and Practical Implications

By combining ideas from risk perception, technology acceptance models, and trust theory, this study adds to the body of knowledge about how consumers accept new food technologies. The research combines cognitive, emotional, and social factors to better understand how people judge nanomaterials in food. It does this by using established frameworks like the Technology Acceptance Model (TAM) and the Theory of Planned Behaviour (TPB). It goes beyond traditional models that focus on rational decision-making by showing how perceived risks, ethical concerns, and trust in institutions have a big impact on how consumers accept something. In doing so, it sharpens and places these ideas in the context of nano-enabled food technologies.

The thesis also goes against the common belief in food technology literature that people are sceptical because they don't know enough. Instead, it shows that a lack of trust in regulatory oversight and unclear risk communication is often more important. This discovery forces researchers to rethink and expand the theoretical frameworks that guide studies of how consumers behave. Instead of thinking of the public as uninformed or resistant to new ideas, the study sees them as rational people who are dealing with uncertainty with limited but emotionally and socially relevant information. This change encourages future theoretical work to include a wider range of factors, such as cultural sensitivity, the impact of the media, and past experiences with other new food technologies like GMOs or food irradiation.

This research provides key insights for everyone involved in the food industry—whether for a producer, a marketer, or a regulator. It's about guiding the responsible use of nanotechnology, making sure it's rolled out thoughtfully. It emphasises how important clear, honest, and targeted communication is. When done right, it doesn't just inform people; it helps them feel confident and enabled to make well-informed choices about the food they eat. Businesses must actively cultivate trust through open labelling, candid communication, and proactive engagement with consumer concerns; they cannot rely solely on scientific validation to ensure acceptance. According to this thesis, early public involvement in the innovation process through educational campaigns and participatory platforms can greatly increase acceptance and decrease resistance.

To gain acceptance, companies will have to make use of clear communication strategies, consumer involvement in the innovation processes at an early stage, and stringent labelling. Regulators should create clear criteria for how to assess risks and how labels should be read. Not doing this is part of what leads people to distrust novel products. It is important to engage stakeholders, especially consumer organisations, scientists and food producers, to enhance credibility and trust. A clear language to communicate the risks and benefits of nanomaterials in food is necessary. Over time, this can reduce opposition from the market and create opportunities for its application in food safety and sustainability innovations through nanotechnology.

These insights can assist regulating agencies in formulating policies more in line with people's concerns and diverse cultural viewpoints. Filling the gap between the perception of risk vs. actual data offers a different approach to the problem, which can be as simple as better labelling of nano-enhanced products, provision of safety information that is not laden with jargon or even partnering with the constituents for the development of governance models. Moreover, the research teaches us that perceptions across various regions and cultures differ greatly, and that underscores the fact that a universally aggregated strategy is not feasible–policies and campaigns tailored to communities are essential. In the end, this reframes the problem of how to funnel excitement about food nanotech innovations while adhering to societal values, ensuring that such innovations prove to support the growth of the market and public health. The food industry must be careful to weigh both the benefits and risks for consumers of nanomaterials. Although nanotechnology holds promise for food safety, waste reduction, and added nutrition, these goals are only attainable if development remains aligned with societal preferences. Transparency, education, and participation of all stakeholders are important to manage perceived risks so that science in this area will lead to accepted and trusted consumer food products.

8.2 Limitations and Future Research

While this study provides a systematic summary of consumers' perceptions and risk evaluations of food nanomaterials, it lacks the following aspects: First, it relies solely on secondary data from a systematic literature review. The absence of primary empirical research data means the study cannot assess contemporary consumers' perceptions or behaviour patterns. Hence, the study will not evaluate how the actual tangible exposure to nano-enabled food products affects consumer acceptance. Second, the review contains only articles in English published between 2013 and 2024. It disregards older literature and some useful insights available in non-English scholarly work, which may lessen the international relevance of the conclusions drawn. This is important for many regions that differ in culture and region, so the scope of this research is limited in focus. Third, the study does not account for unsupported consumer segments such as those residing in lower-income and rural regions. These consumers probably have more defined views on food safety and technology, but the literature is lacking in this field. This is important because it demonstrates the lack of understanding about how socio-economic elements influence risk perception and acceptance.

To further sustain and build upon the arguments made in this thesis, future research should acquire primary data using surveys, interviews, or experimental methods. Trust, risk, communication, and emotional response analysis regarding nanotechnology in food require deeper investigation through empirical approaches, holistic captures oscillating consumer perception dynamics. The scope of studies should be broadened in terms of culture and language to diversify and reflect more global viewpoints. Cross-country and regional studies would demonstrate how trust in regulation and cultural perspectives influence the acceptance of nanofoods through a comparative research approach.

Underrepresented or vulnerable groups should be included in future work on these concepts, in addition; including their insights fosters responsible, socially innovative frameworks and approaches. It is essential to study the public's acceptance and resistance of nanotechnology in comparison with past technologies, such as GMOs, to identify prevailing patterns. Filling these gaps would enable the development of robust theoretical frameworks and practical approaches to the effective and safe advancement of food technologies in future research.

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Appendices