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Review

The Historical Evolution of Food Science: A Comprehensive Review

Snigdha Chetia [1], C. Nickhil [1], Sankar Chandra Deka [1,*]

[1] Department of Food Engineering and Technology, School of Engineering, Tezpur University, Assam, India.
* Correspondence: sankar@tezu.ernet.in

Scopus Author ID 6602881252

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Abstract: Food Science has a rich history intertwined with scientific advancements that have impacted food safety, quality, productivity, and shelf life, thereby shaping the modern food industry. Over time, food science has grown focusing on allied disciplines like environmental health sciences, geography, sociology, and anthropology, highlighting the interdisciplinary nature of food systems science. Food science as a career reveals the need for a tailored curriculum, research programs, and teacher training to grow the next generation of food scientists. The evaluation of food science can be interpreted as a dynamic story of scientific progress, interdisciplinary, educational initiatives, and a commitment to a sustainable and innovative food industry. Hence by digging into food science's historical roots, scientists can extract knowledge to inform current practice, drive future innovation, and tackle the changing challenges in food systems and nutrition. This comprehensive review emphasizes the importance of integrating historical insights with contemporary advancements to foster a sustainable and forward-thinking food industry.

Keywords: Food safety; Productivity; Hydrodynamics; Rheology; Sustainability; Innovative food industry

1. Introduction

Food science is a complex story of technical advancements, cultural shifts, and the pursuit of food safety and quality. Food science started with the need to produce safe and healthy food. Early food preservation technologies emerged out of survival needs, laying the foundation for fundamental principles of food processing and safety. Food science has evolved due to the continuous desire for a safe, abundant, and good food supply which has resulted in the development of several food processing technologies [1]. Among the recent developments, intelligent food packaging has become very important. Smart sensing technologies are changing the way we monitor food quality and safety, extending shelf life and giving consumers real-time information on food products. The demand to improve the nutritional content of food has led to research on new delivery systems for bioactive compounds. This means delivery systems need to be developed for the popular functional foods with several health benefits [2]. This aligns with the bigger push for personalized nutrition where new nutritional assessment tools are being developed to adjust dietary recommendations to individual needs, as [3] mentioned. Technology and nutrition is a more holistic approach to food science with a focus on consumer health and safety. This paper brings together several academic views to trace the history of food science from the beginning to the present (Fig. 1). Plus, biotechnology has had a big impact on the history of food science. Advances in industrial microbiology and biotechnology have changed food production and safety, fermentation processes, GM organisms, and food preservation and quality control. The use of microorganisms in food creation started in the 19th century and was a game changer in food research. This historical approach shows how understanding molecular-level biological processes drives innovation and better food products. Food science is fundamentally interdisciplinary, combining chemistry, biology, nutrition, and engineering to investigate food's physical, biological, and chemical properties and can be called the biggest interplay between technology, societal needs, and scientific research. This integration allows food scientists to address complex issues related to food safety, preservation, processing, and nutritional value, thereby ensuring a safe and nutritious food supply for the population [1]. The historical evolution of food science illustrates advances in numerous scientific areas and their applications in food technology and safety. As [1] point out, the major purpose of food science is to establish and maintain a safe, plentiful, and healthy food supply based on fundamental scientific and technical principles. This concept emphasizes the importance of understanding the biochemical changes that occur during food preparation and preservation, as well as how dietary choices affect human health. Engineering is critical in food science, pushing the development of new technologies that improve food safety and quality. Techniques such as high hydrostatic pressure processing, for example, help to reduce microbial contamination while preserving the nutritional and sensory qualities of food [4]. Such interdisciplinary approaches are crucial for cultivating a thorough understanding of food science among students and future professionals in the field [5].

Food safety has become a hot topic in food science, especially with recent foodborne disease outbreaks. Research shows that having food safety standards in place is critical to public health. For example, education and training for food handlers is key to compliance with safety measures as shown in recent research highlighted the importance of education in preventing foodborne disease. Successful food safety governance requires coordination among many stakeholders including government agencies, consumers, and industry groups. This is because food safety issues require more holistic approaches that bring together different perspectives and skills (Fig. 1). Food science has evolved with technology and research methods. This is further highlighted by the increasing complexity of food supply chains which requires a deep understanding of food safety standards and quality assurance systems [6]. Preservation methods like drying, salting, and fermenting were the key to extending shelf life and safety in ancient times. These early methods laid the groundwork for modern food science which applies science to food safety and quality. Meanwhile, Food processing technology has played a big part in this evolution. For example, the invention of high hydrostatic pressure (HHP) processing in the 1990s was a major step forward, you can preserve food and keep nutritional and sensory qualities [4]. This non-thermal technology reduces microbial contamination and extends shelf life, showing how current advances build upon and improve older methods [4]. The 20th century was a big revolution in food science driven by economic growth and scientific progress. Food processing innovations like freezing, chilling, and automation changed the industry, and made food safer, more nutritious, and more convenient for consumers. In recent years food science has evolved by embracing a multidisciplinary approach and modern technology. The evolution of food science shows the quest of humanity for better nutrition and safety through innovation. Preservation methods from ancient to modern biotechnology, the field has always changed to meet society's needs and to encourage scientific growth. This review summarizes key points from various studies to show the evolution of food science through the ages. It illustrates the progression from early human societies, where agriculture was conducted manually with simple tools, to the use of animals for plowing fields, and finally to modern farming techniques that utilize machinery.

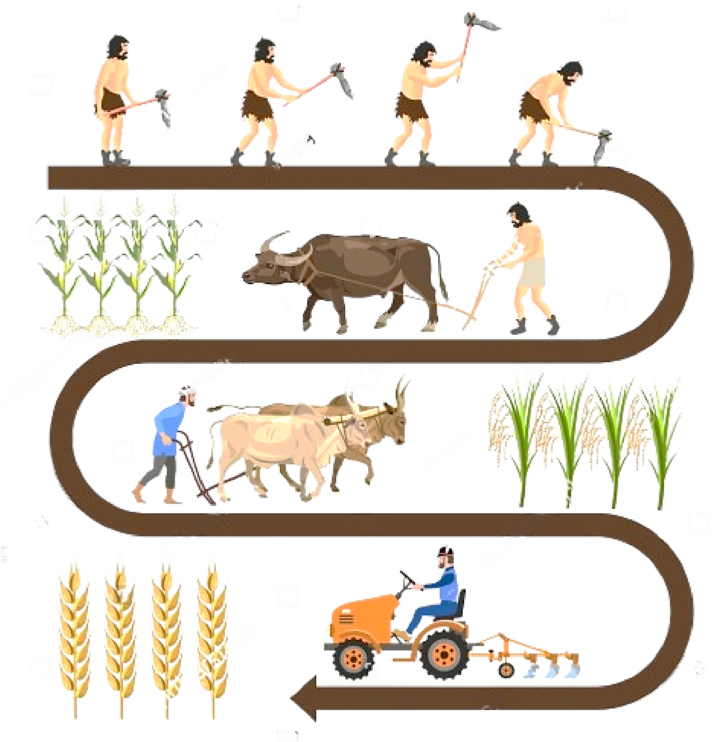

Figure 1. The historical evolution of agriculture [66]

2. Ancient and Early Food Practices

2.1. Prehistoric and Ancient Methods

In the early human cultures foraging, hunting and gathering was the norm before moving to more complex farming (Fig. 1). Dietary preferences, food preparation methods and plant and animal domestication changed dramatically during this period. Table 1 shows different eating traditions from ancient civilizations. Prehistoric cultures relied heavily on natural preservation methods and drying was one of the first. In Mesopotamia barley, rice, corn, flax, date palms, lentils and chickpeas were staples of the diet. Sun-drying helped them to keep food for longer and to survive famine (Table 1). This gave them food independence and laid the ground for more advanced preservation methods [7]. Drying as a preservation method with its long history over the years shows its importance as a response to environmental problems throughout human history [7]. Similarly, nutrition and food safety also has rich historical roots. For example, the ancient fermentation method in Indus Valley Civilization was to preserve food and prevent rot which was critical to ensure food safety [8] (Table 1). Fermentation not only extended the life of food but also the nutrition of it by encouraging good bacteria growth. Ancient food preparation involved many processes including grinding and fermentation to preserve and boost nutrition. Fermentation was a key strategy to preserve food and improve its taste and nutrition [8]. This goes back to ancient times and has been part of the creation of many food products including drinks. Early civilization didn't have scientific understanding of microbe operation but they used it efficiently. Cultural has a big impact on the evolution of food science. Social and political framework has often influenced the food traditions of ancient civilization. This type of influence can be seen in the ancient Chinese civilization where political ideology had a big impact on food culture, controlling dietary habit and the availability of food. The intersection of food, culture and politics shows that food science is not just a technical field but is closely tied to the fabric of society (Table 1).

2.2. Agricultural Revolution

The Agricultural Revolution brought various changes in the human history from moving population from being nomadic hunter gatherer lifestyles to permanent agricultural communities (Fig. 2). This changed everything starting from eating patterns, social structures and economic systems. Agriculture allowed for the domestication of plants and animals, more food and permanent communities. This was not only good for population growth but also for the formation of complex communities and trade networks which were key to the development of food science. During this time staple crops like wheat and rice were introduced and food security and diet preferences changed. The Green Revolution of the 1960s and 1970s brought high yielding crops that increased food availability in places like India and SE Asia and led to food self-sufficiency [9]. But monoculture has raised questions about sustainability and ecological balance and we need to rethink agriculture. Domestication gave us a more stable food supply which allowed population growth and the formation of complex societies. Humans selected features that increased output and resilience and we got our modern crop and animal breeds. A recent study found specific genes that were important in the domestication process. But the Agricultural Revolution had far-reaching consequences that went beyond food production. As you can see in Fig. 2, many factors drove this revolution including big environmental changes as people started to manage ecosystems to suit their needs. The transition to agriculture also marked the beginning of a complex relationship between humans and the environment, laying the groundwork for future agriculture and societal institutions.

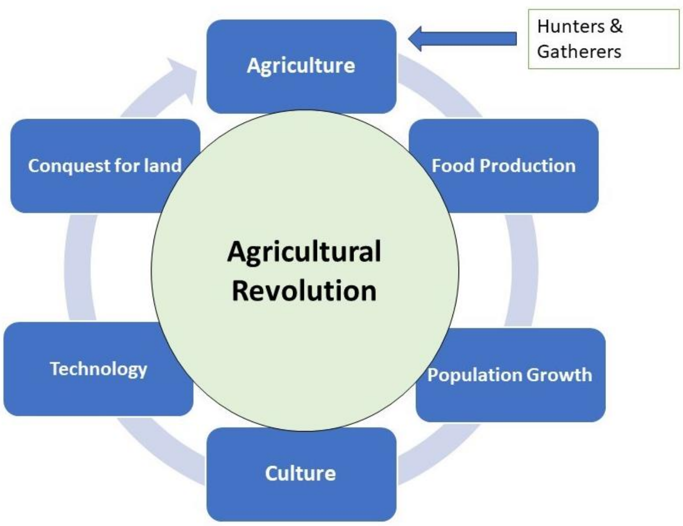

Figure 2. Agricultural Revolution and its corresponding factors (Self designed)

Table 1. Different ancient civilizations representing various food practices

Regions/ Civilizations	Food Practices				References
	Common Foods & Diet	Food Preservation Technique	Livestock & Animal Husbandry	Agriculture	
Mesopotamia	Barley, Rice, Corn, Flax, Date palms, lentils and chickpeas, beans, onions, garlic, leeks, melons, eggplants, turnips, cucumbers, apples, grapes, plums, figs, pears, dates, pomegranates, apricots, pistachios, herbs, and spices.	Drying was a traditional method for preserving fruits, vegetables, and meats for long-term preservation. Grains were kept in granaries to keep them pest and moisture-free. Another method for preserving vegetables such as cucumbers, onions, and garlic was pickling, which involved using vinegar or brine.	Sheep, Cattle, Goats, and Equids were raised primarily for their wool, an essential material for Mesopotamian workshops, but also for their meat and milk. Apiculture was developed in Mesopotamia at the beginning of the 1st millennium BC.	Early Mesopotamians built canals and dikes to control river flow, allowing them to extend arable territory and boost grain harvests. Mesopotamian agriculture was characterised by animal husbandry and crop rotation, which improved soil fertility and production. The use of animal excrement as fertiliser considerably increased nitrogen levels in the soil, resulting in healthier crop development.	[10], [11], [12]
Ancient Egypt	Food and drink in ancient Egypt were based on barley and wheat, the main crops grown along the Nile. The Egyptian diet consisted of bread, alcohol, and vegetables.	Sun drying was a common method employed by the ancient Egyptians, particularly for dates and figs, which were important components of their diet. They used a variety of	Domesticating animals such as sheep, goats, chickens, and cattle was crucial to the agricultural methods that kept ancient Egypt's civilization alive. Evidence	The Egyptians grew a broad range of crops, including garlic, onions, and legumes such as chickpeas and lentils, which helped to	[9],[13]

Regions/ Civilizations	Food Practices				References
	Common Foods & Diet	Food Preservation Technique	Livestock & Animal Husbandry	Agriculture	
		techniques, including smoking, curing, salting (both wet and dry), and mixing them to preserve meat. They also employed techniques like curing with lard, beer, or honey, and pemmicaning.	suggests that Egypt had a livestock agricultural society as early as 1840 B.C., and important archaeological finds attest to the existence of domestic animals and other livestock at this period.	maintain a healthy diet. Agriculture was strongly related to religious ideas and activities, as seen by the worship of fertility and harvest deities. Osiris, for example, was worshipped as the deity of agricultural wealth.	
Indus Valley	Wheat, barley, peas, sesame, and cotton were major crops grown by the Indus Valley Civilization's population. Fish played an important role in their nutrition.	The Indus Valley Civilisation used a variety of food preservation techniques, including drying, fermentation, effective water management, and specialised storage vessels. The planned placement of granaries inside metropolitan areas demonstrates a well-organised system for storing excess grains throughout harvest seasons, assuring food supply over time.	The Indus Valley Civilization's sustenance tactics relied heavily on animal domestication, particularly the river buffalo (Bubalus bubalis). In addition to buffalo, they kept cattle and sheep, though sheep were less common.	Advanced water management systems, including as canals and reservoirs, allowed for successful irrigation of crops like as wheat, barley, and cotton, contributing to the civilization's agricultural prosperity.	[13], [14]

Regions/ Civilizations	Food Practices				References
	Common Foods & Diet	**Food Preservation Technique**	**Livestock & Animal Husbandry**	**Agriculture**	
Ancient China	The traditional Chinese diet consisted mostly of basic grains such as rice and wheat, supplemented by a variety of vegetables and few animal-based items. Rice was a staple of the diet, especially in southern areas, where it was consumed in a variety of forms such as rice porridge and sticky rice. Wheat was more popular in northern China, where it was frequently used to make noodles and dumplings.	Ancient Chinese food preservation techniques were varied, including fermentation, drying, and the use of natural preservatives. Fermentation, one of the earliest preservation processes, was widely utilised for a variety of foods, including vegetables and grains, and was essential for survival during severe seasons.	Domestication of animals, particularly cattle, sheep, and pigs, was critical to the agricultural methods that maintained the expanding population and urbanisation over dynasties.	Ancient Chinese agriculture began with the cultivation of rice and millet, followed by the introduction of wheat, all while reacting dynamically to climate variations. The introduction of wheat (Triticum spp.) to China marks another significant milestone in ancient agricultural techniques.	[15]

3. Medieval and Renaissance Era Developments

Cooking and food storage systems were developed in ancient civilisations for life and nourishment. Even the archaeological findings show that they used boiling to cook starchy foods, as seen in the residue analysis of cooking pots that showed changes in starch granules due to boiling [12]. This understanding and knowledge of cooking improved not just the taste but also the safety and nutrition of food. Food preservation techniques improved with time and as society evolved, especially in the medieval and Renaissance periods. Smoking, pickling, and spices were necessary to extend food life. Among these, smoking not only added flavor but also acted as a preservation method by inhibiting microbial growth [15]. Pickling which uses acidic solutions was a popular way to preserve vegetables and meats, reduced decay and foodborne illness [12]. Spices also add flavor and antibacterial properties to keep the food safer. Moreover, during the medieval period the major issue was to ensure food security in the face of seasonal changes and thus the need for proper food storage methods became crucial. Methods such as the fermentation and drying were perfected during this era [16]. Furthermore, knowledge of appropriate storage temperatures, and the growth of more sophisticated food handling procedures became more crucial as populations grew and urban areas expanded [17].

4. The Industrial Revolution and Modernization

The Industrial Revolution was a turning point in food production that turned traditional farming methods into an industrial system with the arrival of mechanization and new processing techniques. The revolution was fueled by the need to feed an urbanizing population which required advances in food preservation and safety. Technologies like canning, refrigeration, and pasteurization were key advances in the field of food processing to improve food safety and shelf life in the late 19th and early 20th centuries. The focus of food science over the years shifted towards the study of several health effects of food. There are several examples such as the prioritizing of hygiene and modern scientific methods by the Soviet Union in the 1970s to improve food quality [15]. This era saw an increase in knowledge of the link between food processing and public health and stricter food safety regulations were established. [18] also emphasized the importance of food safety saying that science and technology have played a critical role in ensuring food systems are safe, nutritious, and accessible. Modernization has given us a global view of food safety as seen in the regulatory frameworks established to address the complexity of food supply chains. According to [19], the implementation of Hazard Analysis and Critical Control Point (HACCP) systems is a big step forward in food safety management. Figure 3 shows the 7 principles of HACCP. These systems are designed to identify and manage hazards throughout the food production process to ensure safety requirements are met from farm to table. Digitalizing food systems has given us new ways to ensure food safety and traceability. As mentioned earlier, the blockchain technology incorporation provides new and smart ways to monitor food quality and safety throughout the supply chains which also corresponds to increased consumer satisfaction and confidence [20]. In this way, the data-driven solutions are being used to solve food safety problems by using this technological progress in the modern world.

Figure 3. The 7 Principles of Hazard Analysis and Critical Control Point (HACCP) Plan

4.1. Technological Innovations

Throughout history, different technical breakthroughs have revolutionized the landscape of food production and consumption. The food sector changed dramatically in the second part of the twentieth century, owing to economic affluence and technological development (Table 2). This age saw a substantial shift in food processing technology, which sought to not only preserve food but also improve its nutritional content and palatability [3]. The incorporation of contemporary scientific procedures into food production was most visible during the late Soviet period when experts emphasized the relevance of chemical components and microbiology in generating healthier and more sustainable food items. Hygiene became a primary emphasis of food production, indicating a more comprehensive understanding of food safety and quality [21].

Nicolas Appert invented the canning technique in the early nineteenth century, which is regarded as one of the most significant achievements in food science history. Appert's discovery invented about 1809, was motivated by the necessity to preserve food for extended periods, notably for military purposes, as indicated by its early usage in feeding troops during the Napoleonic Wars [22]. This procedure entailed sealing food in airtight containers, which efficiently avoided rotting while retaining its look and nutritional value [23]. Canning quickly became commercialized, with Peter Durand patenting the use of metal cans in 1810, significantly enhancing food preservation techniques [24].

Louis Pasteur laid down the scientific foundations of canning and also stated in his discovery that microorganisms were the cause of food spoilage. Pasteur’s work ultimately led to the development of pasteurization and other technologies that improved the safety and shelf life of canned foods [25]. The marriage of food science and microbiology laid the groundwork for modern food preservation methods, and the importance of scientific research in food safety and quality [25]. Canning not only revolutionized food preservation but also put prepared meals into the commercial market. By the late 19th century canned goods were everywhere, and customers had convenient options that kept the virtues of fresh vegetables [26]. This changed eating habits and food access, especially for groups like sailors and soldiers who needed long term food supply [26]. Canning has evolved into the 21st century with advances in materials and processes that improve canned goods [27]. Nicolas Appert’s invention of canning is a milestone in food science history, and the inclusion of scientific ideas in food technology has not only changed food storage but also impacted consumer behavior and the whole food industry.

4.2. Advances in Food Chemistry and Nutrition

The discovery of functional foods that provide health benefits beyond nutrition is a game changer in food research. Functional fruits and vegetables contain bioactive compounds like carotenoids, dietary fiber and phenolics that promote health and disease prevention [28]. Research has shown that combining dietary components with individual health profiles can improve nutritional outcomes, hence the importance of precision nutrition in disease prevention [29]. Food and nutrition science plays a bigger role in addressing health issues, with transdisciplinary applications in fields like pharmacology and genetics [30]. The emergence of omics technology, especially metabolomics has changed food research by allowing us to study metabolic reactions to dietary intake. Metabolomics can uncover biomarkers for disease risk and improve food quality and safety [31]. It also ensures food authenticity and quality control [32]. Same with nutrigenomics or the integration of genomics in nutrition science that looks into how foods interact with genes to affect health outcomes, we need to understand these relationships so we won't give out wrong dietary advice [33]. The promise of genomics in the food industry is increased food production and safety [34].

Pasteur's discovery changed our understanding of fermentation and the role of microbes in food processing and has long-term implications for food science. Pasteur developed the germ theory of disease in the mid 19th century and proved that some microbes can cause spoilage and disease. His work established yeast as a key player in fermentation, especially his work on tartaric acid in 1857 which was a big leap forward in understanding microbial interactions in food [33]. This led to better quality of fermented products and the need for microbial population management in food safety. Pasteurization developed in 1864 is one of Pasteur's biggest contributions to food science. This is heating food products at a certain temperature for a certain time to kill unwanted bacteria while retaining nutrients and flavor [35]. Pasteurization is now crucial for food safety especially in dairy industry as it reduces the risk of foodborne diseases associated with raw milk [35]. This method is widely used and modified for various food products including juices and canned goods. Also, Pasteur's work laid the foundation for microbiological standards in food processing and resulted in rules and laws for food safety.

Table 2. Technological evolution in the history of food science highlights key advancements across different periods

Sl. No.	Period	Technology/Innovation	Description/Impact	References
1.	Prehistoric Era	Fire Control	The discovery of fire allowed early humans to cook food, improving safety, digestibility, and flavor	[36]
		Stone Tools	Used for hunting, gathering, and processing food, including grinding grains.	[37]
2.	Neolithic Period	Agriculture	Development of farming and domestication of plants and animals, leading to stable food supplies.	[21]
		Pottery	Enabled food storage and cooking, preventing spoilage and extending the shelf life of food.	[36]
		Fermentation	Early methods of preserving food through fermentation, leading to products like beer, bread, and yogurt.	[38]
3.	Ancient Civilizations	Irrigation	Advanced irrigation techniques (e.g., Mesopotamia, Egypt) that enhanced agricultural productivity.	[21]

		Milling	Development of simple mills to grind grains into flour, making grains more consumable.	[39]
		Salting and drying	Techniques for preserving meat and fish, critical for long-term food storage.	[40]
4.	Middle Ages	Spices and Trade	Increased trade of spices and other foodstuffs, leading to cultural exchanges and the spread of culinary practices	[31]
		Food Preservation	Advances in pickling, smoking, and fermenting to preserve food through long winters and transport.	[36]
		Bread Ovens	The development of dedicated ovens for baking, improving the quality and consistency of bread.	[41]
5.	Renaissance	Distillation	Refinement of distillation techniques, leading to the production of spirits and improved preservation methods	[42]
		Sugar Refinement	Development of sugar refining techniques, making sugar more widely available and altering diets and food preparation.	[43]
6.	18th Century	Canning	Invention of canning by Nicolas Appert, allowed food to be stored for long periods without spoiling	[44]
		Chemical Leavening Agents	Introduction of baking powder and soda, revolutionizing baking by making it easier to produce leavened bread and cakes.	[45]
7.	19th Century	Pasteurization	Louis Pasteur's method for preventing spoilage and killing harmful microorganisms in beverages like milk and wine.	[46]
		Refrigeration	Development of ice houses and later mechanical refrigeration, drastically improved food preservation and transport.	[47]
8.	20th Century	Food Fortification	Introduction of vitamins and minerals into staple foods to prevent deficiencies (e.g., iodized salt, fortified flour)	[44]
		Convenience Foods	The emergence of pre-packaged, processed foods (e.g., canned soups,	[48]

			frozen meals) to meet the demands of fast-paced modern life.	
		Genetically Modified Organisms (GMOs)	Introduction of genetically engineered crops to improve yield, pest resistance, and nutritional content	[48]
9.	21st Century	Food Safety Technologies	Advanced food safety protocols, including the use of HACCP (Hazard Analysis and Critical Control Points) and food irradiation to reduce contamination risks	[49]
		Sustainable Agriculture	Adoption of technologies and practices to reduce environmental impact (e.g., precision farming, vertical farming	[49]
		Plant-Based Alternatives	Development of plant-based meat and dairy alternatives using advanced food processing techniques to meet growing demand for sustainable and ethical food choices	[49]

4.3. Emergence of Food Science as a Discipline

Food science became a separate subject due to many key milestones, starting in the 19th century with breakthroughs in nutrition research. This brought together food knowledge, health and human physiology, and our understanding of food's nutritional value and impact on health. As the food system became more industrialized there was a need for experienced people to monitor production and safety and so food science became a separate academic discipline. Food science has become a broad discipline drawing on chemistry, microbiology, engineering, and nutrition to navigate the complexity of food and its importance in our lives [50]. This broadening of the discipline also brought new food processing methods and regulations. The use of science in food safety and quality control became critical, especially with the rise of food-borne outbreaks in the late 1800s [50]. Food science programs in universities have boosted the subject by giving students skills in food safety, processing, and nutrition [51]. Modern-day food technology comprises the use of various modern technologies such as nanotechnology and microfluidics which are being investigated for food quality improvement and nutritional delivery systems [52]. The continuous development of food science education and outreach programs aims to engage the younger generation and increase awareness of the subject and ensure a steady supply of qualified workers in the industry [53].

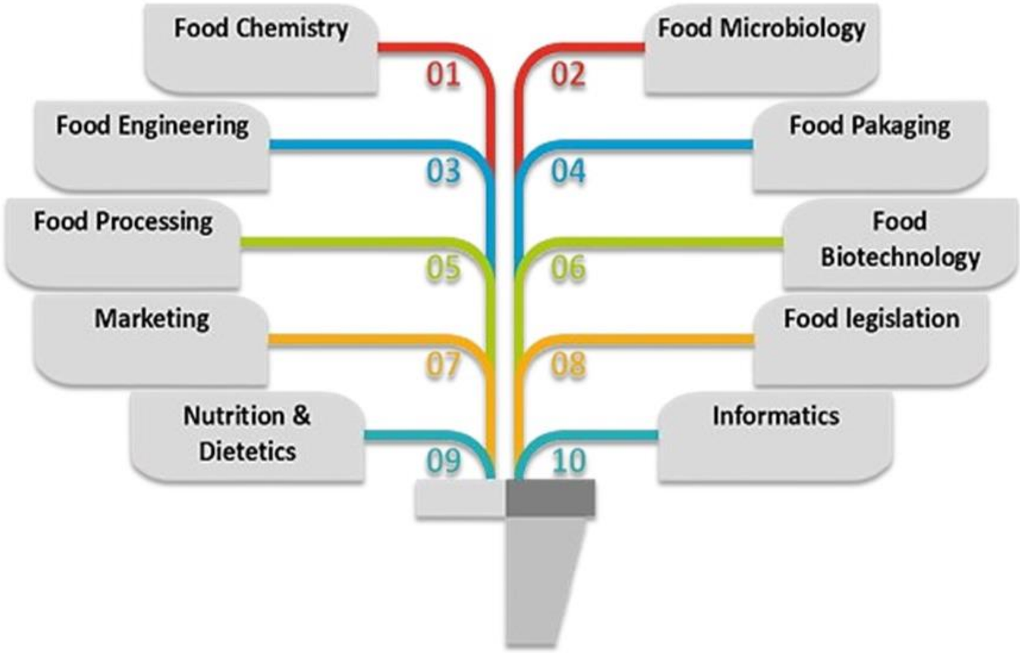

Figure 4. Different Disciplines of Food Science

4.4. Government Regulations and Public Health

In the early days of food regulation, especially in the late 20th century, governments were mainly focused on food safety crises. A big milestone was the introduction of food safety regulations in the UK in 1990 which formalized food governance [54]. Table 3 shows the key legislation and activities that have impacted food safety and science in India and the US over time. Food governance is very complex with new food systems, especially with the introduction of new technology and globalization of food supply chains. The rise of online food delivery has added new issues, like knowledge asymmetry between customers, producers, and regulators, making the regulatory environment more complex [55]. This has led to calls for more government control and the development of integrated food safety management systems that can adapt to new threats [54]. Including food science in regulatory frameworks has been critical so that food industry experts know how to meet the requirements. Having food science education standards has equipped graduates to navigate the complexity of food legislation and contribute to public health [54]. This education is key to developing a workforce that can address today’s food safety issues and consumer protection.

Table 3. Key regulations and acts that have shaped food safety and food science in India and the United States over the years

Year	Regulation	Country	Description	Impact on Food Science	Reference
1862	Establishment of the USDA	United States	The U.S. Department of Agriculture (USDA) was established to oversee agriculture, food safety, and nutrition.	Pioneered government involvement in food safety, leading to future regulations and inspections.	[56]
1906	Pure Food and Drug Act	United States	Prohibited the sale of adulterated or misbranded food and drugs; laid the foundation for the FDA.	Marked the beginning of federal regulation to ensure food safety and labeling.	[42]
1938	Federal Food, Drug, and Cosmetic Act (FDCA)	United States	Expanded FDA's authority; required pre-market approval for drugs and set safety standards for foods.	Strengthened food safety, leading to safer food production and better public health outcomes	[57]
1947	Prevention of Food Adulteration Act	India	Introduced to combat the growing concern of food adulteration in India.	Laid the foundation for food safety regulations, emphasizing quality and purity.	[57]
1954	Prevention of Food Adulteration (PFA) Act, 1954	India	Enforced stricter standards for food quality and safety	Brought significant improvement in monitoring and controlling food adulteration	[57]
1958	Food Additives Amendment	United States	Required FDA approval for food additives; established the Generally Recognized as Safe (GRAS) list.	Ensured that food additives were scientifically evaluated for safety before use in food.	[58]
1960	Color Additive Amendments	United States	Required safety testing of color additives used in foods, drugs, and cosmetics.	Enhanced safety standards for artificial colors used in food products.	[59]
1970	Environmental Protection Agency (EPA) Creation	United States	Established to oversee environmental and human health risks, including pesticide regulation	Led to stricter pesticide controls, reducing harmful residues in food.	[60]

Year	Regulation	Country	Description	Impact on Food Science	Reference
1990	Nutrition Labeling and Education Act (NLEA)	United States	Required nutrition labeling on most packaged foods and standardized health claims.	Improved consumer awareness about nutrition and influenced healthier eating habits.	[61]
1996	Food Quality Protection Act	United States	Overhauled pesticide regulations to focus on children's health, setting stricter safety standards	Reduced pesticide exposure in food, particularly protecting vulnerable populations.	[62]
2006	Food Safety and Standards Act	India	Replaced the PFA Act, consolidating various laws related to food safety.	Established the Food Safety and Standards Authority of India (FSSAI) to regulate food safety.	[63]
2011	Food Safety Modernization Act (FSMA)	United States	Shifted focus from responding to contamination to preventing it; expanded FDA’s inspection powers.	Enhanced the safety of the U.S. food supply through proactive risk management.	[63]
2011	FSSAI Guidelines on Food Additives	India	Detailed guidelines on the permissible use of food additives and contaminants.	Ensured that food additives are safe for consumption and standardized across the country.	[59]
2013	Food Safety and Standards (Packaging and Labelling) Regulations	India	Set regulations for the packaging and labeling of food products.	Mandated clear labeling of ingredients, nutritional information, and allergen warnings.	[64]
2018	GMO Labeling Law	United States	Required labeling of genetically modified organisms (GMOs) in food products.	Increased transparency, allowing consumers to make informed choices about GMOs in their food.	[65]
2018	Food Safety and Standards (Organic Foods) Regulations	India	Introduced standards and certification for organic foods	Promoted the growth of the organic food sector and ensured consumer trust in organic labels	[66]
2019	Food Safety and Standards	India.	Introduced guidelines for fortifying foods	Aimed to address nutritional deficiencies	[67]

Year	Regulation	Country	Description	Impact on Food Science	Reference
	(Fortification of Foods) Regulations		with essential nutrients.	in the population, particularly in vulnerable groups.	
2020	FSSAI's Eat Right India Movement	India	Launched to promote healthy eating habits and food safety awareness.	Focused on improving public health through better food choices and safer food practices.	[68]
2021	Ban on Trans Fats	India	FSSAI imposed a limit on industrial trans fats in foods to 2%.	Aimed at reducing the risk of heart disease and promoting healthier food options.	[69]

5. Late 20th Century Developments

5.1. Post-War Innovations

The late 20th century was a big moment for food science, with technical advancements, knowledge of nutrition, and emphasis on food safety. Science became more integrated into food production and processing and it changed everything. During this time biotechnology advanced big time, especially with the creation of genetically modified organisms (GMOs). This changed agriculture by increasing crop yields and pest and disease resistance through advances in molecular biology and genetic engineering, allowing scientists to add more genetic traits to plants and animals. This has far-reaching implications beyond agriculture, raising ethical and safety issues around food consumption and the environment. This led to the creation of regulations to protect the consumer and the environment [70].

And by the late 20th century there was more understanding of nutrition and its impact on health. The scientific community was saying that diet was the key to preventing chronic diseases like obesity, diabetes, and heart disease. Research on nutrition and health outcomes led to the development of dietary guidelines and public health campaigns to promote good eating [71]. After several high-profile foodborne illness outbreaks, food safety became the top priority, and stronger regulations and HACCP (Hazard Analysis and Critical Control Points) systems were introduced to identify and manage risks in food manufacturing. This was critical to rebuilding public trust in food safety and was driven by increasing scientific knowledge of viruses and pollutant [72]. The inclusion of research into food safety showed the importance of evidence-based approaches to public health. Consumer attitudes changed in the late 20th century, they wanted transparency on labels and an interest in food origin and manufacturing process. This was part of a larger movement for sustainability and ethical consumption which forced food scientists to look at alternative production methods like organic farming and sustainable fishing [73]. This was the watershed moment in food science, technical innovations, more understanding of nutrition, better food safety, and changing consumer tastes changed the food industry and set the stage for future advances in food science and public health.

5.2. Nutritional Science and Public Awareness.

Food science, especially in nutritional science and public awareness, has gone through many changes influenced by research, dietary guidelines and public health initiatives. This change reflects our growing understanding of the complex relationship between diet and health and disease prevention. Initially dietary recommendations were all about preventing nutrient deficiencies. Dietary guidelines have evolved from addressing specific nutrient needs to broader dietary patterns that promote overall health. The USDA has played a big role in shaping dietary recommendations since the early 20th century and has adapted its guidelines to address emerging health concerns and advances in nutritional science. The USDA's food guidelines started with the Food Guides in 1916 which provided basic nutritional advice to the American public (Table 3). Over the years these guidelines evolved into more structured formats like the Food Guide Pyramid in 1992 and the more recent MyPlate. These changes were driven by our growing understanding of nutrition and its impact on health and the need to address public health issues like obesity and chronic diseases [74].

Food additives are part of modern food production to enhance colour, flavour and texture to increase shelf life and nutritional profile. This is represented by food additives, preservatives and fortification [75].Consumer's concerns about safety and health risks have led to the use of these substances and for open communication and regulation [76] Historically, food preservation methods such as salting, drying and fermenting have evolved over time, from ancient methods to chemical preservatives and modern technology like freezing and ultrasound [77] In case of public health emergency, fortification of food with vitamins and minerals is proven to be effective in addressing nutritional deficiencies in communities. This method was developed from fortifying basic food such as salt with iodine and bread with folic acid which is popular to more innovative alternatives that add bioactive compounds and probiotics to everyday meals [78].

Alternative protein sources are the proteins that are derived from plants and are completely vegan. Most of the protein sources are meat alternatives mimicking the exact taste and texture of meat. With increasing demand for sustainable food over the years, there is a wide range of protein alternatives in the market for human consumption [79]. A rapidly expanding range of products is being developed, based on plants, cells, mycoprotein, and precision fermentation, that mimic the taste, look, and smell of animal meats and dairy products. Across a broad range of products, plant-based meats require 47–99% less land and 72–99% less water, emit 30–90% fewer greenhouse gas (GHG) emissions, and cause 51–91% less aquatic nutrient pollution compared with factory-farmed animal meat using lifecycle analysis [80]. The main cause of this is the high environmental footprint of meat. Nutritionally, if compared, the plant-based meat is similar in terms of macronutrients to animal-based meat, but they fail to mimic the nutritional complexity of plant-based meat. Microalgae can also contribute high-quality dietary protein for vegan and vegetarian diets, or in regions of low access to animal proteins [81]. Macroalgae have traditionally been used globally in human food, both as direct consumption (e.g., sushi) and as a processed product (e.g. flakes, gelling agents), with recognized immunity, skin benefits, and growth regulation properties for humans [82]. There is increasing interest in their use as an alternative protein, particularly green and red algae species with high-protein contents. Protein alternatives have considerable potential for sustainably delivering protein for food and feed and could lead to significant reductions in climate and land use impacts.

5.2. Globalization and the Food Industry

Over the past 100 years food science has moved from basic preservation techniques to biotechnological applications driven by the need for safe, nutritious, and convenient food. Food science as a discipline emerged in the early 20th century when the focus was on food preservation methods such as canning and refrigeration. As stated previously, technologies such as freezing, chilling automation, and computerization of food production were considerable changes in the second part of the century. Also, the field of food science has evolved to include complicated processing methods to meet the requirements of a rising global population by improving food quality on a large scale. In the 1970s the rise of biotechnological life sciences was a key moment in food science as noted by. This was a period of technological breakthroughs that enabled the development of various downstream applications in food technology particularly in biochemistry [83]. Biotechnology has been incorporated into food science and has shown significant success in shifting consumer demands for novel food items such as plant-based alternatives which are both ethical and sustainable solutions [84]. Demand for these products has increased in recent years as consumers are moving towards health-conscious and environmentally friendly eating habits [4].

For the past two decades, among plant-based candidates, soyabean has also emerged as a widely consumable food and has potential due to its high protein content (40-45%) [85], complete amino acid profile, functional versatility and established agricultural presence. However due to its increased demand, the soyabean as a protein alternative have given rise to monoculture [86]. This refers to the utilization of vast expenses of land for the cultivation of a single crop over the years. This has been particularly evident in countries like Brazil, Argentina, and the United States, which collectively account for over 80% of global soybean production (FAO, 2020). Monoculture can have a negative impact on soil degradation, pest vulnerability, deforestation, and habitat loss [87]. These ecological consequences undermine the sustainability claims often associated with plant-based diets that rely predominantly on soy. To address the over-dependency of soy and reduce the risk of monoculture, researchers have now started calling for other protein alternatives such as pulses, millets, algae and single-cell proteins, and insect protein [86]. With such steps and balancing the plant protein narrative, these challenges can be addressed by diverse, locally adopted crops and a resilient agricultural system.

The Food and Agriculture Organization (FAO) has strongly emphasized the utilization of insect-based protein alternatives, particularly in Africa, citing the high feed conversion efficiency, low environmental impact, and nutritional value of edible insects (FAO, 2013). Moreover, insects provide a remarkable advantage over the conventional alternatives because edible insects are rich in high-quality protein (30-80%) [88] with all the essential amino acids. They are rich in micronutrients such as iron, zinc, calcium, and vit B. They also have Healthy fats such as polyunsaturated fatty acids (PUFAs) and lauric acid (especially in black soldier fly larvae), making it a serious contender in the future of global food security [89]. Combining the wisdom of traditional entomophagy with modern food printing technology, we have the tools to reinvent insects as acceptable, nutritious, and sustainable protein alternatives.

6. Future Directions and Challenges

Food science is biology, chemistry, and engineering to improve food safety, quality, and sustainability and get around the old systems. One of the most exciting is lab-grown meat, produced through cellular agriculture to reduce the environmental impact of traditional livestock and animal welfare issues. Lab-grown meat has been shown in studies to reduce greenhouse gas emissions, land use, and water use by a lot compared to traditional meat production. Bioprocessing and tissue engineering are key to optimizing lab-grown meat output while ensuring nutritional adequacy and consumer appeal [90]. Food waste is a big problem for the food industry, made worse by the Covid-19 pandemic. The FAO estimated 820 million people were undernourished in 2018 so we need better waste management solutions [91]. Food waste management technology innovations are key to turning surplus food into value-added products, reducing waste, and increasing food security [92];[93]. SFSCs can increase resilience by encouraging local production and reducing dependence on global unstable networks [94]. And the 4th industrial revolution with IoT, AI, and big data offers a lot of opportunities for food industry innovation [95]. These technologies improve operational efficiency, food safety, and resource management so that sustainable food systems can be achieved [96]. Industry 4.0 can solve food security problems by monitoring and managing the supply chain [97]; [98],[100]. Automation and data analytics for example can produce and reduce waste food for those who need it. The Covid-19 pandemic has exposed the weaknesses of food systems so we need revolutionary policies that prioritize sustainability and resilience [99]. This has also given birth to new organizational structures to increase food availability for low-income people like new distribution models and community involvement initiatives that prioritize inclusion and sustainability [101].

This interdisciplinary approach helps us understand food systems and tackle global issues like food security, health, and sustainability. Cross-disciplinary collaboration is a big challenge in food science research. For example, omics technologies (genomics, proteomics, and metabolomics) have changed the game with “Foodomics” and we can now assess food composition and health implications and hence improve food safety and quality [102]. Also, collaboration between nutritionists and data scientists has given us new ontologies to understand food information on social media, and how interdisciplinary research can inform public health [103]. A big problem in food science is the need for ethical innovation as new technologies emerge. “Foodomics Think Tanks” can facilitate the discussion on the ethics of these innovations by bringing together experts from food science, medicine and bioengineering [104]. The UN Sustainable Development Goals are about sustainable practices so we need to integrate social science into food system research. Food science has a lot to offer to address food poverty and health inequities. The concept of food sovereignty which means communities designing their food systems is getting more and more into public health discourse [105]. This shift means localized food systems that are culturally relevant and nutritionally sufficient, hence better health outcomes for communities[106,107]. Also, the recognition of food science as a career is growing and can attract a new generation of researchers and practitioners.

Multidisciplinary Domains

This research covers the domains: (a) Chemistry and Biochemistry, (b) Engineering and Technology, (c) Nutrition and Dietetics, and (d) Agricultural Sciences.

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Conflicts of Interest

The authors declared that there is no conflict of interest.

Declaration on AI Usage

This manuscript has been prepared without the use of AI tools.

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