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Review:

The applications of Fuzzy Logic models on food and marine food products

Übersichtsarbeit:

Die Anwendung von Fuzzy-Logik-Modellen auf Lebensmittel und Meeresfrüchte

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Summary

With the developing technology, methods for determining the quality of food products by fast, easy, cheap, and reliable methods are preferred. Fast techniques have many advantages over traditional methods in terms of usability in determining the quality and safety of food products. Furthermore, they also have significant advantages because they can be used in a variety of issues such as predicting the quality, shelf life, and risk evaluations of food products in mathematical models, which have become increasingly popular in recent years. Developing fast methods and the advantages of using constantly developing mathematical methods together with these methods in all sectors, especially food and marine food products, will increase their preferences in the future as well as today. The fuzzy logic approach is one of these recommended mathematical methodologies. Therefore, on the importance of subject the usage of fuzzy logic model, their applications on food and marine food products and the latest studies on this subject were included in this review. In the future, it is expected that upgraded versions of the fuzzy logic method will eventually replace the fuzzy logic versions currently in use.

Keywords: Fuzzy Logic model, food products, marine food products

Introduction

Energy is generally used in the seafood sector for machinery and equipment handling activities such as refrigeration, freezing, cooling, drying, and heating. Similarly, a large amount of clean water is used to clean machinery and plant and for operations such as raw material defrosting, salt splashing de-icing, and washing. Therefore, it is essential to concentrate primarily on the significance of water and energy use optimization in the seafood industry, the current trend of water and energy management practices, its environmental implications, the seafood-water-energy nexus, use pattern, and optimization methodologies (Murali et al., 2021). Optimization approaches are applied to identify the best option of the methods. The research combine experimental design methods with artificial intelligence (AI) tools to build a multi-objective optimization methodology. The capability of this hybrid AI methodology is evaluated in the best control variable design to acquire the best performance of the methods (Karambeigi et al., 2023). User-friendly and low-cost portable devices with quality estimate capabilities would be beneficial for real-time quality measurement of food products (Meenu et al., 2021). Handling, processing, and storage processes from catch/harvest to the customer can have an important impact on the safety and quality of fishery products. The retention duration and the temperature of storage of post-harvested fish products are critical elements in maintaining the product‘s final quality (Dutta et al., 2016). The microbial population of all types of food products should be observed concurrently with the estimation of changes that take place in the assimilation and production of some chemical compounds. This can enable assesment of spoilage found or produced during food storage at various temperatures and packaging conditions (Nychas et al., 2008). Introducing new ways for determining the quality and freshness of food products can improve the nutritional value of the entire household food supply. In conjunction with the developed models, might be used as an effective safe method for determining the freshness and quality of food products (Lalabadi et al., 2020). Therefore, the automated vision-based system has many advantages over traditional subjective and instrumental methods in that it is rapid, objective, non-invasive, exact, and economical (Mohebbi et al., 2009). Because they have been established as a promising option for detecting and monitoring food spoilage, instrumental detection devices such as biosensors, electronic tongues, and electronic noses paired with chemometric techniques have received a lot of attention (Ghasemi-Varnamkhasti et al., 2018). In recent years, statistical predictive models also have been used to determine the optimization conditions of processing and estimate the spoilage and shelf-life of food products (Kılınç et al., 2022a, Kılınç et al., 2022b, Kılınç et al., 2023). A predictive food microbiological model is a mathematical depiction of mechanisms describing a microorganism’s growth, survival, inactivation, or metabolic reaction. It is used in the food sector to anticipate the emergence of food pathogens and to aid in the evaluation of food safety. Furthermore, it decreases the amount of costly and time-consuming laboratory experiments. However, proper statistical analysis is required at all stages of model construction and validation (Jaiswal and Jaiswal, 2015). Many processes are too complex to manage statistically; nonetheless, humans succeed by employing basic rules of thumb derived from their own experiences. Fuzzy logic mimics human reasoning by making conclusions based on imperfect information. Unlike traditional techniques, which need a mathematical grasp of the system, fuzzy logic is a method of processing that allows for the modeling of complicated systems using human knowledge (Diaz-Cortes et al., 2017). In recent times many studies also have been done about fuzzy logic and combined models used with fuzzy logic applications. Some of the studies made about using fuzzy logic were given as follows. Fuzzy logic regulation of relative humidity in microwave drying of hawthorn was investigated (Li et al., 2021). The fuzzy logic method was also used to simulate temperature control and processing time in tulip production (Pacco, 2022). In addition to this, the detection of supply-demand relationships using a fuzzy logic system was used to study dynamic multi-objective balancing for online food delivery (Zhen et al., 2022). In light of the importance of the subject, the purpose of this review is to provide an overview of some research and applications of fuzzy logic models on food and marine food products.

The Fuzzy Logic models

Fuzzy Logic is a mathematical approach to modeling and analyzing uncertain and imprecise data. While traditional logic focuses on precise values such as true (1) or false (0), Fuzzy Logic deals with uncertain situations. This allows us to better understand and solve complex real-world systems and problems (Klir et al., 1995).

Fuzzy Logic has emerged to mimic human thinking and decision-making processes. Humans can make decisions based on vague and uncertain information. For example, they may describe the temperature of an object as ”hot“ or ”cold“, but it can be difficult to provide a precise temperature value. Fuzzy Logic provides a conceptual framework to address such uncertainties.

Fuzzy Logic models are built on fuzzy sets, fuzzy rule bases, and fuzzy inference mechanisms. Fuzzy sets represent mathematical structures for representing uncertain data. Fuzzy rule bases, collect fuzzy rules in an ”if-then“ format. Fuzzy inference mechanisms process input data using these rules to produce output values (Ross, 2010).

Fuzzy Logic has a wide range of applications in various fields. It has been successfully used in control systems, artificial intelligence, data analytics, and decision support systems. Fuzzy Logic models provide an effective tool for modeling complex systems and processing uncertain data (Klir et al., 1995).

In recent years, there have even been developments in Fuzzy Logic models such as fuzzy neural networks and genetic algorithms that combine fuzzy reasoning with other computational techniques (Pedrycz and Gomide, 2007). These hybrid models are advanced capabilities for solving complex problems in different domains and continue to evolve. The flexible nature of Fuzzy Logic has led to the development of various modeling and analysis methods for different types of problems. Commonly used Fuzzy Logic Model types are as follows:

Fuzzy sets and Fuzzy Logic control systems

This approach is used for modeling and decision-making with uncertain data. Fuzzy sets are used to represent uncertain data and inferences are made by applying fuzzy logic rules on these sets (Zadeh, 1965). Fuzzy logic control systems are one of the practical applications of this approach and are widely used in the control of industrial processes (Mamdani and Assilian, 1975).

Journal of Food Safety and Food Quality 75, Heft 2 (2024), Seiten 35–64

Fuzzy combination models

This modeling approach is used to combine the outputs of systems with multiple inputs. Fuzzy combination models are created by combining different fuzzy sets and fuzzy inference rules. This method provides an effective tool for integrating uncertain data from multiple data sources (Wang and Mendel, 1992).

Fuzzy set-based classification models

This modeling approach is used to solve data classification problems. Data are transformed into fuzzy sets and classification is performed on these fuzzy sets. This approach allows the handling of uncertainties in classification problems (Bezdek, 1981).

Fuzzy association analysis models

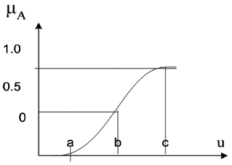
This modeling approach is used in areas such as data mining and pattern recognition. Fuzzy association analysis is used to identify relationships and matches in a data set. This method provides an effective tool for identifying relationships and discovering patterns among uncertain data sets (Huarng and Yu, 2003).

Fuzzy optimization models

This modeling approach is used to solve optimization problems. A fuzzy optimization is an effective tool for problems with uncertain objective functions and constraints. This method is used to optimize problems using a combination of genetic algorithms and fuzzy inference techniques (Kandel, 2001).

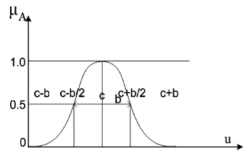
S- membership function

$$S(u;a,b,c)=\begin{cases}0 & \mu<a \quad \text{for}\\ 2[(u-a)/(c-a)]^2 & a\le u\le bb \quad \text{for}\\ 1-2[(u-c)/(c-a)]^2 & u\le cu>c \quad \text{for}\\ 1 & \text{for}\end{cases}$$



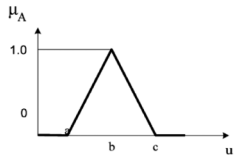
π- membership function

$$\pi(u;b,c)=\begin{cases}S(u;c-b,c-b/2,c) & \mu<c \quad \text{for}\\ 1-S(u;c,c+b/2,c+b) & \ge c \quad \text{for}\end{cases}$$



Triangular membership function

$$\check{U}(u;a,b,c)=\begin{cases}0 & \mu<a \quad \text{for}\\ (u-a)/(b-a) & a\le u\le bb \quad \text{for}\\ (c-u)/(c-b) & \le u\le cu> \quad \text{for}\\ 0 & c \quad \text{for}\end{cases}$$



Trapezoidal membership function

$$Y(u;a,b,c,d)=\begin{cases}0 & \mu<a \quad \text{for}\\ (u-a)/(b-a) & a\le u\le bb \quad \text{for}\\ 1 & \le u\le cc> \quad \text{for}\\ (d-u)/(d-c) & \upsilon\le du\le d> \quad \text{for}\\ 0 & \text{for}\end{cases}$$

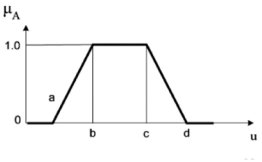


FIGURE 1: *Most known membership functions*

The theories of the Fuzzy Logic models

Fuzzy sets are represented as μA(x) membership function. The μA(x) is the membership function degree of a point x in the A fuzzy set. The case of μA(x)=1 indicates that x is a definite member of the A fuzzy set, while the case of μA(x)=0 indicates that x is outside the A fuzzy set. Every value between 0 <μA(x) <1 is an indeterminate value of x membership in the A fuzzy set. Therefore, imprecise quantities are represented by fuzzy sets specified by membership functions (Geurge, 1995; Wang, 1997).

Membership functions frequently used in practice; s-function, π-function, triangular, trapezoidal, exponential, and Gaussian. The most known ones are given in Figure 1 (Samanta, 2018; Gupta et al., 2023).

Implication functions used in fuzzy logic are Mamadani, Larsen (Product Rule), Zadeh, and Boolen. The most widely used ones are Mamadani, Larsen, and Tsukamoto implication functions. In the inference method of Mamdani, membership levels in the blur unit are related to the membership function of output by minimum relation operator. In the Laren's method, the membership levels of blurring unit are correlated with the output membership function by using the algebraic product operator. On the other hand for Tsukamoto's inference method, the membership levels from blurring unit are related with the inverse of the output membership function. Fuzzy relation operators used in inference methods of Mamdani, Larsen, and Tsukamoto are stated in equations 1–3 below, respectively (Jang et al., 1995).

Here, μ_X and μ_Y are the input membership functions, μ_Z

$$Z_i = (\mu_{xi}(u) \cap \mu_{yi}(v)) \cap \mu_{zi}(w) \quad (1)$$

$$Z_i = (\mu_{xi}(u) \cap \mu_{yi}(v)) x \mu_{zi}(w) \quad (2)$$

$$Z_i = f^{-1}\mu_{zi}(\alpha_i) = f^{-1}\mu_{zi}(\mu_{xi}(u) \cap \mu_{yi}(v)) \quad (3)$$

is the output membership functions, Z is the inference result, and i is the rule order.

The importance and usage of Fuzzy Logic models

Intelligent computer programs capable of estimating and forecasting future states might be useful as ‚software sensors' when confronted with unpredictable and complex bioprocesses. Fuzzy logic has been demonstrated to be an effective tool for dealing with ambiguous and partial information, as well as for integrating human expert knowledge into modeling processes (Eerikainen et al., 1993). This technique for dealing with fuzziness in subjective assessment data to principal component analysis and correspondence analysis is applied. Fuzzy sets can be defined from some point in a data space in the present method, and the fuzzy parameters of a statistical model are found using a linear programming approach or the technique of least squares (Nakamori and Ryoke, 2006). This fuzzy

logic system that used the most attractive characteristics such as dissolved oxygen, temperature, pH, nitrates, salinity, and turbidity as fuzzy inputs to forecast the best combination of environmental circumstances that promoted the growth of marine foods such as shrimp. Furthermore, this study also demonstrated the design of this system and how it could be extended to incorporate sensors for real-time effective control and monitoring (Adetunji et al., 2022). In comparison to quality personnel assessment, a fuzzy logic system could also be developed and utilized to classify food quality. The topping area percentage index had the lowest uncertain degree value, showing that it had the least amount of fuzziness. The classification error for the 5 (five) personnel classifications was 24%. When only 2 (two) categorization levels were evaluated (acceptable and faulty quality), an accuracy of 100% was obtained (Sun and Brosnan, 2003). In one research, customer clustering was reported to be a necessary step in the reduction of the level of difficulty of enormous-scale logistics system optimization. Customers‘ attributes were described using variables under minor and major factors. Then a fuzzy integration approach based on trapezoidal fuzzy numbers was utilized to map the criteria to the upper hierarchical criteria. To divide customers into the multiple clusters, an Axiomatic Fuzzy Set-based fuzzy clustering technique was not only created but also the clustering validity index was intended to analyse the performance of the suggested method for identifying the best clustering solution (Wang et al., 2014). Using this fuzzy logic model, numerous machining parameters may be examined. This type of model can be built on universe portioning, rule generation, rule combination, fuzzy relations, and the link between input and output membership functions. Drilling machines can commonly be used in industry to create various types of holes. In addition to this, the fuzzy logic predicted value has been indicated to be close enough to the experimental value (Karuppusammy et al., 2022).

In a typical robotic control system, fuzzy logic has been used at multiple hierarchical levels. Task design, monitoring the system, which includes self-tuning and self-organization, filtering of data and preliminary processing, and in-loop direct management are the four broad levels of application that may be distinguished. Although the requirement for fuzzy logic is recognized mainly at higher levels of the control system, current implementations concentrate mainly at the lowest possible level, which may be due to efficiency rather than need (Silva, 1995). The Deep Neuro-Fuzzy System has also been used favorably in a variety of applications. However, the model confronts two challenges that are firstly a dataset with a good few characteristics rapidly improves the fuzzy rule-base; and secondly, fuzzy rule-base parameters are being optimized using the gradient descent attitude, which has the issue of local minima. To improve the model‘s accuracy by proposing the Arithmetic Optimization Algorithm. The results of applying the algorithm for feature selection reported not only lowered the cost of implementing a large dataset but also the Arithmetic Optimization-based deep neuro-fuzzy system surpassed the usual method with 95.14% accuracy compared to 94.52% (Talpur et al., 2022).

The applications of Fuzzy Logic models on food products

Managing sensory qualities from the fabrication stage in an autonomous framework is a critical issue for organizations in the food industry, but it is not an easy task (Perrot et al., 2004). Fuzzy logic is currently a broad field of study, with numerous tools developed during the previous decade. Several authors who have concentrated on different applications created expressly for this task have highlighted its deployment in food quality control for the food industry. This is especially relevant when considering the reasoning process of operators and specialists, as articulated in linguistic terms (Perrot et al., 2006). End-products in the food industry have to maintain a balance of sensory, hygienic, and technological features. Managing these qualities from the manufacturing phase in order to control them is a difficult challenge. Many manufacturing procedures are currently heavily dependent on the expertise and knowledge of the operator, which no system would be able to replace in the near future. Therefore, the quality of a food product cannot be represented solely through the sharp adjectives ‚good‘ or ‚poor,‘ but rather requires an infinite sequence of possibly imprecise categories to be adequately defined and ultimately controlled (Perrot and Baudrit, 2013). Automation in the food sector necessitates intelligent and practicable strategies for replacing human intelligence with machine intelligence. Quality control checks characteristics of products that cannot be precisely quantified, hence the link between the attribute parameters is ambiguous. Machines can check the visual features of the goods more correctly and swiftly (Rezagholi and Hesarinejad, 2017). By carefully assessing the food conditions when the food is received, the Fuzzy rule-based Reasoning engine may give recommendations on the ideal place for inventory conditions. Monitoring the quality control of receiving operations and food storage conditions in the storage area can be accomplished with the system‘s support. It supplies consistent and regular Quality Assurance Guidelines for monitoring quality, resulting in increased satisfaction among customers and a lower failure rate (Lao et al., 2012). In the last few decades, significant performances have been made to address these challenges through the use of intelligent soft computing, revealing substantial possibilities for integrating human knowledge and learning methodologies into more effective process control procedures of systems of biology. Control systems based on fuzzy logic, in particular, have a significant potential for managing complicated manufacturing processes and dealing with fragmented process information (Birle et al., 2013). The Fuzzy logic systems are well suited to the collection of many data sources to feed multi-variable systems that support decisions (Petropoulos et al., 2017). This innovative fuzzy logic method of application is also capable of being utilized to rank samples quickly and consistently, without the complexity of the traditional similar value approach (Bose and Bhattacharjee, 2018). One work described the creation of a novel fuzzy-QFD-based methodology for defining customer ratings of food goods. The method‘s key novelty was the use of fuzzy logic to handle the problem, which was common in many decision-making procedures, of dealing with data derived from subjective vocally expressed judgments that could not be dealt with the mathematical models. The purpose of this study was to put to the test a combined assessment strategy based on quality function deployment and a fuzzy logic method for evaluating which aspected of extra virgin olive oil influence the most proper consumer acceptance of the product (Bevilacqua et al., 2012).

Many applications have been found in the fuzzy logic methodology compared with other models and hybrid applications with advanced technologies for food products. The hybrid e-nose-fuzzy logic methodology repla-

Journal of Food Safety and Food Quality 75, Heft 2 (2024), Seiten 35–64

ced current chemical approaches and was integrated for online quality assessment of the frying disposal time of cooking oils (Upadhyay et al., 2017). Additionally, the storage quality of shelled peanuts was evaluated utilizing this hybrid technique. The described method was reported to be used as a non-destructive alternative to standard tests in agro-industrial settings to achieve the following harvest quality of shelled peanuts (Raigar et al., 2017). Using the fuzzy fusion technique, the authors attempted to fuse sensory elements. The temporary datasets received from the tongue, and electronic nose separately were used to create a broad fuzzy rule base. It has been reported that the fuzzy system model, which has a much simpler model than the neural network, provides reliable prediction. However, both systems had stated to be an advantage. A fuzzy neural network (FNN) model was also constructed in order to advance a better classifier. Furthermore, the authors reported that the model worked with transient reactions and did not use any data compression techniques (Banerjee et al., 2013).

The safety and quality characteristics of food products are seen as critical issues all over world as they are closely tied to health and societal advancement. In this study, Fourier transform infrared (FTIR) spectroscopy with the help of a neuro-fuzzy identification model was used to address the rapid and non-destructive detection of meat spoilage bacteria during aerobic storage condition at cool and different changing temperatures. The proposed modeling approach could be regarded as a good alternative technique for estimating meat rotting accurately indicated by the authors (Kodogiannis and Alshejari, 2014). In one study, the projected moisture content was examined to automatically halt the fixing process of green tea. To optimize the entire fixation process, a fuzzy logic controller was built to manage continuously the microwave power, and the temperature. The end product quality was substantially enhanced due to the intelligently managed fixation in terms of taste, liquor color, appearance, residue color, and odor, when compared with the original product (Song et al., 2023). Sensory evaluation has been commonly used in lots of industrial domains, particularly in the marketing, product design, and quality inspection. Historically, the only instrument for assessing and modeling the sensory data provided by panelists, experts, and customers was factorial multivariate approaches. These strategies are effective for solving some problems, but they can result in the loss of critical information. In this case, innovative ways based on intelligent procedures such as fuzzy logic, data aggregation, neural networks, clustering, and classification have been used to address imprecision, and uncertainty in sensory evaluation. These new strategy can be used in conjunction with the traditional ones to extract important information from sensory input (Zeng et al., 2008). Fuzzy sets and neural network techniques were utilized to determine food process control set points in order to produce products with desired sensory qualities. To analyze sensory responses, fuzzy sets were used, and neural networks were used to describe the interactions between process and sensory variables. The findings showed that the fuzzy set idea and neural network techniques had significant potential in sensory quality-based food process control of rice cake production, with sensory assessments evaluated in the fuzzy method (Kupongsak and Tan, 2006). Besides, when the process was complex, one of the viable options was to use a fuzzy control system. According to the input parameters such as food surface cracks, rheological measures, and food thickness, the fuzzy control system (software) established in this study could govern roll gaps. The outcomes indicated that an optimal food sheeting method could be accomplished by implementing the fuzzy logic system. When compared to the results of a non-fuzzy system, the material was rolled in less time without sacrificing food quality (Mahadevappa et al., 2017). The purpose of one work was to create a user-friendly and dependable tool based on the fuzzy logic multi-criteria decision-making to accurately assess the quality of wine depending on chosen grape properties. The fuzzy logic multi-criterion decision-making tool may be able to incorporate grape quality indicators at harvest into a single index, enabling growers of grapes and producers of wine with a precious tool for categorizing wine quality (Petropoulos et al., 2017). The fuzzy logic analysis of food samples also revealed that the product generated under optimal conditions as determined by restricted optimization utilizing a genetic algorithm was actually superior to other samples. Taste, color, scent, and mouthfeel were the most important qualitative criteria for the traditional dairy product in India in general with the decreasing order (Mukhopadhyay et al., 2013). One report looked towards the optimizing the preparation and fuzzy analysis of sensory data of bread samples made using wheat flour and fermented chickpea flour. The adequacy of the optimized formulation was confirmed by fuzzy analysis of the same combinations (The optimum ratio was xanthan gum: wheat flour: chickpea flour: = 2:80:18 (w/w) (Shrivastava and Chakraborty, 2018). In another report, bread samples were made with two composite and wheat flour to compare the quality of the loaves. The sensory analysis was performed to determine the suitability of these samples. This sensory study's analysis was carried out by applying fuzzy logic. Sensory investigation revealed that the general acceptance of bread samples made from composite flours was nearly equal to that of wheat bread (Singh et al., 2012). For modelling the correlation between overall acceptability and sensory characteristics of different types of fried donuts (36 samples) by using the Fuzzy linear regression. In this model, the assumption was built with independent variables with triangular fuzzy numbers (Zolfaghari et al., 2014). The fuzzy logic framework was created using the Mamdani inference system and compared to the Takagi-Sugeno-Kang inference for determining food preservatives. The Fuzzy Mamdani-based inference system outperformed the Takagi-Sugeno-Kang inference system. Furthermore, it was well-suited to human-related problems, particularly identifying the number of food additives for preservation with fast, simple formulation, friendly usage, and accurate alignment with standards (Mavani et al., 2021). Additionally, for rapid identification of tobacco origin, a new broad learning system that it included Takagi-Sugeno fuzzy subsystem was developed. The suggested method gave rise to progressive learning, which provided the network's weight matrix after a relatively the minimum amount of calculations results in a significantly faster training time for the model, with roughly 3 s for the additional stage of training. The findings from experiments suggested that this fuzzy subsystem could obtain characteristics from near-infrared data and increased the efficiency of recognition significantly (Wang and Yang, 2023). Various fuzzy algorithms for mature tomato classification were used and examined in accordance with hardness, size, and fruit color combinations. By exposing materials to the Instron compression test as well as panelist

rates, fuzzy membership functions of hardness were created. The results showed that combining the previously mentioned tomato features with fuzzy membership criteria could precisely categorize the tomatoes into the appropriate market groupings (Nassiri et al., 2022). Using Fuzzy logic analysis, the sensory qualities of the produced cookies were compared to imported biscuits and two high-energy cookies currently available on the market. To prevent teenage malnutrition, linear programming, and fuzzy logic were determined to be simple methodologies that could be used in any World Food Program endeavor to create cheap, as well as high-energy foods (Varghese and Srivastav, 2022). The primary issue with industrial pizza production was the standardization of processing. This study attempted to offer a possible standardisation of the production technique using the fuzzy logic system by iden-

TABLE 1: *Some of the applications of Fuzzy Models on the food products.*

Fuzzy models and usages	The results and advantages of the studies	References
A fuzzy model for controlling the food system	Short processing time to determine parameters of the food quality including food safety was assessed	Mahadevappa et al., 2017
Fuzzy logic analysis for optimizing the quality	The taste was determined as the most critical quality characteristic for the optimization of the traditional dairy product	Mukhopadhyay et al., 2013
The fuzzy logic multi-criterion decision-making tool for determining wine quality	This method was determined a valuable tool for categorizing wine quality	Petropoulos et al., 2017
Fuzzy analysis for optimizing formulation	The formulation of bread samples was optimized	Shrivastava and Chakraborty, 2018
Fuzzy logic analysis for acceptability of sensory analysis	The acceptability of wheat bread was carried out nearly the same as the bread made using composite flours	Singh et al., 2012
Fuzzy linear regression model for evaluating the acceptability of the sensory characteristics of fried donuts	This function revealed that aroma was no effect on overall acceptability, whereas flavor was the strongest effect on donut desirability in accordance with the products with a porous and softer texture were more acceptable	Zolfaghari et al., 2014
The fuzzy logic analysis with the Takagi-Sugeno-Kang, and Mamdani inference systems for the food preservation	The food preservatives ratios used in the processed fruits were successfully determined by using the fuzzy logic	Mavani et al., 2021
Fuzzy subsystem including with Takagi-Sugeno inference for identification of tobacco origin	The fuzzy subsystem identified characteristics from near-infrared data and increased the efficiency of recognition importantly	Wang and Yang, 2023
Fuzzy algorithms for classification of the mature tomato	Various fuzzy algorithms for the tomato classification were used for evaluating hardness, size, and color properties correctly	Nassiri et al., 2022
Fuzzy logic analysis for comparison of the sensory qualities of the produced cookies with imported biscuits and two high-energy cookies on the market	It was determined to be a simple method that could be used in any World Food Program endeavor to create cheap, as well as high-energy foods	Varghese and Srivastav, 2022
Fuzzy logic analysis for standardization of the production technique of pizza	The large scale could be useful in designing because of the easy to use application in both industrial and handmade pizza production via the management of this system	Pilli, 2022
Fuzzy logic analysis to examine the sensory qualities of a functional and healthful product made with soymilk as the basic ingredient	The organoleptically acceptable beverage with beneficial components was assessed according to fuzzy logic analysis	Kumar et al., 2021
The fuzzy logic for evaluation of the sensory score of sourdough bread production	The fuzzy logic sensory score of bread produced from 20% foxtail flour and 1% guar gum was discovered to be the most desirable formula (0.7221)	Das et al., 2021
Fuzzy logic analysis using a 5-point fuzzy logic scale for sensory properties of high-pressure applied on litchi juice and mango pulp	The consumer's preferences on the relevance of sensory qualities were acquired as crisp integers correctly	Kaushik et al., 2015
The Fuzzy TOPSIS model for determining the quality of items made with Apple Ber powder	This model could help the manufacturers for choosing the right balance of ingredients and developing the consumer acceptability of the product overall	Mathangi and Maran, 2021
The adaptive neuro fuzzy inference system (ANFIS) to evaluate the overall acceptability of ice cream	This model could be used to predict the average sensory acceptance of food products and comparable items	Bahram-Parvar et al., 2017
The fuzzy technique to characterize the sensory qualities of pickles during storage	The pickles' sensory qualities were assessed during storage (0–90 days) at 30-day intervals using fuzzy logic analysis. Conventional pickles formula and the kinetic assessments of phytochemicals throughout storage were obtained	Gupta et al., 2023
MLR, ANFIS, and ANN models were used to predict the antibacterial activities of GPE, and GPP against pathogenic *E. coli* and *S. aureus*	The ANFIS model outperformed the MLR and ANN models in predicting the antibacterial effects of GPE and GPP against pathogenic bacteria *(E. coli, S. aureus)* in the soup	Sagdıc et al., 2012
Neuro-adaptive learning approaches were incorporated into the fuzzy logic method for analyzing risk variables for *S. Typhimurium* infections	The results show that the proposed approach was more effective than the traditional fuzzy logic model	Qin and Yang, 2011
The neuro fuzzy identification model addresses the very rapid, and nondestructive detection of spoilage bacteria of meat during aerobic storage condition at cool and abusive temperatures	The proposed modeling approach could be regarded as an alternative technique for estimating meat spoilage accurately	Kodogiannis and Alshejari, 2014
Fuzzy logic controller to optimize the entire fixation process of green tea	The end product quality was substantially enhanced due to the intelligently managed fixation using this controller	Song et al., 2023

Journal of Food Safety and Food Quality 75, Heft 2 (2024), Seiten 35–64

tifying single and interactive impacts of processing variables that greatly influenced pizza quality. Panellists preferred samples with low dough moisture (44%) levels and baked at a medium oven (350°C) temperature, which was an overall judgment>7. The validation of the algorithm employed in this study on a large scale could be useful in designing an easy-to-use application for both industrial and handmade pizza production via management cellphones or software (Pilli, 2022). The purpose of one study was to apply fuzzy logic analysis to examine the sensory qualities of a functional and healthful product made with soymilk as the basic ingredient. By using the fuzzy systems and programs, three samples from the same combination were evaluated to eliminate any errors. Furthermore, it was reported to be a potential vegan and lactose-intolerant alternative to milk beverages. It was also reported to be an organoleptically acceptable beverage with beneficial components (Kumar et al., 2021). Sourdough bread was made with millet flours (foxtail, barnyard, tiny, and kodo) in this work because of its slow digestion of starch and low glycemic reaction. The foxtail sourdough bread had the highest fuzzy logic sensory score (0.9895), so more research was done on bread produced with varied foxtail concentrations (50%, 40%, 30%, and 20%). (Das et al., 2021). Using fuzzy logic, the sensory properties of high-pressure processed litchi juice, and mango pulp were examined by comparing with untreated and thermally treated samples. Using a 5-point fuzzy logic scale, judges' preferences on the relevance of sensory qualities were acquired as crisp integers rather than the other variables. The sensory quality of samples was then compared by using the estimated sample ranking, overall sensory scores, similarity values, overall membership function, and quality features. Among the sensory characteristics evaluated, „taste" was deemed extremely important for both litchi juice and mango pulp. Furthermore, changes in the sensory properties of both fruit products after processing were linked to changes in physicochemical parameters (Kaushik et al., 2015). The pot temperature was adjusted throughout the green tea fixation process using an adaptive fuzzy logic control technique. The adaptive fuzzy logic procedure greatly enhanced the end product quality in regards to liquor color, appearance, residual color, and smell (Chen et al., 2022). The quality of items made with Apple Ber powder was assessed in one study. For this reason, a nine-point scale was established to collect expert comments on several aspects that demonstrate the product's quality. The Fuzzy TOPSIS was used to analyze and rank this viewpoint. This ranking was discovered to be valuable for manufacturers in selecting the proper balance of ingredients, as well as developing the overall acceptance of the product by customers (Mathangi and Maran, 2021). The adaptive neuro fuzzy inference system (ANFIS) was utilized in this study to estimate the overall acceptability of ice cream. Consumer approval has been identified as the primary motivator for the product development process. ANFIS used experimental sensory qualities (flavor, body and texture, its viscosity and creaminess) as inputs and independent total acceptance as output. The ANFIS model produced an average error in prediction of overall ice cream acceptability of only 5.11% (Bahram-Parvar et al., 2017).

The fuzzy logic models were also used for determining the antimicrobial activity and preservation of food products. The fundamental idea of mathematical modeling, which can be used to evaluate the impacts of natural antimicrobial agents as food preservation agents (Jaiswal and Jaiswal, 2015). Genomic analysis, molecular simulations and interactions, the docking of molecules, structurally and/or functional class estimation, and quantitative structure-activity connections are all part of the computational method used for antimicrobial agent discovery and design (Hammami and Fliss, 2010). The current study aimed to create stuffed red chilli pickles using a traditional method that was widely used in northern India. To characterize the sensory qualities of prepared pickles during storage, the fuzzy technique was used. Sample 4, which was stored for 90 days had the highest ranking of all four samples and was approved by the sensory panels (Gupta et al., 2023).

ANFIS, artificial neural network (ANN), and multiple linear regression (MLR) models were used to predict the antibacterial activities of grape pomace extract (GPE), and grape pomace powder (GPP) against both pathogen microorganisms *E. coli* and *S. aureus* in the soup (Sagdıc et al., 2012). Neuro-adaptive learning approaches were incorporated into the fuzzy logic method for analyzing risk variables for *Salmonella Typhimurium* infections. With 80% training data, a multi-factor predictive model was created, and the proposed technique was tested with the remaining 20% unexposed data (Qin and Yang, 2011).

The applications of Fuzzy Logic models on marine food products

Fuzzy-Logic Cognitive Maps (FCM) were collected by the authors from multiple groups such as pre and post harvesting sectors, scientists, managers, harvesters, and related persons with environment to assess social agents within social-ecological systems. The authors not only contrasted the maps of stakeholder groups using graph theory indices to characterize the structure and function of the model system, but they also merged stakeholder FCM to build a community map that represents a theoretical model of stakeholder knowledge combination (Gray et al., 2012). An agent-based system for simulating elementary cognitive behaviors was presented in one study. To support cognitive decision-making, numerical data were translated into fuzzy symbolic representations of the surrounding environment, and reasoning rules were integrated into a modified Fuzzy Inference System. The low-level cognitive behavior was translated into a rule-based fuzzy system, and hardware-based experiments were performed to validate the suggested technique's effectiveness (Yuan et al., 2022). In another study, the Fuzzy Logic Adjust (FLC) system was used to adjust the water temperature (29 °C) for maximum growth and quantity of produce. This system offered various advantages over traditional systems, including being very simple, rapid, adaptive, and responding better and faster in all atmospheric conditions. One of the most prominent applications of geothermal heat was in recirculating aquaculture systems (RAS), in which the water temperature was precisely adjusted to provide optimal growing conditions for the environmentally friendly and efficient production of freshwater and marine fish (Farghally et al., 2014). Additionally, the most essential water quality indicators that contributed to algal bloom prediction were identified using machine learning (ML) algorithms by the authors. The ML results revealed that the intricate interplay of nutrients, organic pollutants, and environmental factors drove eutrophication and algal proliferation. Moreover, the ANFIS outperformed the other

models examined due to its consistent and outperforming prediction (Ly et al., 2021). In the other study, heavy metals occurred in the environment as trace elements and water pollutants discharged by industrial activities. This paper showed the creation of the new fuzzy logic approach based on potentiometric measurements obtained with three different miniaturized chalcogenide glass sensors in various heavy metal solutions. Measurements in unidentified single- and multi-component heavy metal solutions were used to illustrate the important validation of the built fuzzy logic algorithm. The program's limitations, as well as a comparison of computed and expected results for the sample composition and heavy metal ion concentration, were demonstrated and addressed (Turek et al., 2009). While aquaculture has been reported to be significantly faster in integrating information mining and ML techniques with sophisticated agricultural systems, the fishing industry has also been indicated to be developed with dependable methods to sort the complications in data collecting and processing (Gladju et al., 2022). The novel fuzzy adaptive jellyfish search optimized stacking system (FAJS-SS) was integrated with the jellyfish search (JS) optimizer, the fuzzy adaptive (FA) logic controller, and the stacking ensemble ML in one paper. The results of analyses revealed that the FAJS-SS predicted more exactly than the other ML systems. Additionally, the FAJS-SS was reported to be useful for engineering fields during the design, and planning phases (Truong and Chou, 2022). The fuzzy based Fish Swarm Algorithm (FSA) was also used in another paper to solve the optimal design of nano-scale circuits. The fuzzy observer in this proposed method was in charge of detecting and preserving the system's state inside the given area. In addition to this, this method was compared to several benchmarks, and the cost, delay, energy, and area characteristics were lowered. Further, the simulation results revealed that the proposed method performed correctly in terms of „energy," „cost," „area," and „delay," where it surpassed others (Zhang and Zhang, 2022).

Food security is a top priority for every government on the planet. However, a variety of factors are making it difficult to meet global food security targets. Global food security is being hampered by certain unprecedented shocks. Various interventions have been implemented to improve food security (Kutyauripo et al., 2023). In addition to this, quality evaluation is also a difficult topic in the food industry in order to achieve the highest level of food safety in accordance with consumer choice (Ali et al., 2020). There have been a raising number of reports of noticed modifications in food safety, especially from a microbiological aspect, as well as quality and yield. For this reason, there is an urgent need for better technologies to foresee the food safety implications. Over the years, advanced technologies have affected many aspects of the food chain, including ocean-to-fork production as well as food safety and quality evaluation and predictions (Karanth et al., 2023). Intelligent evaluation and monitoring of key parameters, as well as food packaging are critical technologies not only for ensuring food quality and safety but also for optimizing packing materials and enhancing the efficiency of cold chain activities (Ren et al., 2021). When transporting several types of food with different handling needs, such as temperature and humidity, the effective distribution of perishable food is critical in the international cold chain network (Tsang et al., 2018). The freshness and quality of fish samples are primarily compromised during the post-harvest period as a result of handling, processing, and storage. The sample's quality may deteriorate as time passes before it reaches the consumers (Issac et al.,2017). Under real cold chain conditions, fish products have a limited shelf life due to quality fluctuations caused

TABLE 2: *Some of the Applications of the Fuzzy Logic models on marine food products.*

Fuzzy models and usages	The results and advantages of the studies	References
Fuzzy preference analysis with geometric Bonferroni inference	The consumer demand was investigated, which was based on a consistent fuzzy preference method with a geometric Bonferroni mean	Cantillo et al., 2021
Fuzzy analysis and D-optimal mixture design for developing plant-based fish analog	The sensory characteristics of the vegan fish analogues were analyzed using a fuzzy scale and the samples were scanned according to their similarity values. The shelf life study was also carried out using an optimized formulation	Patil et al., 2023
Fuzzy logic model (FLM) for assessing fish quality that relies on biogenic amine levels	This model was used to assess the fish quality and the Pearson correlation between storage durations and fish quality	Zare and Ghazali, 2017
Fuzzy logic model (FLM) to investigate the taste quality of *Eriocheir sinensis* gonads after frozen storage	The general taste characteristic of samples could be correctly discriminated against using the fuzzy logic model during frozen storage	Fan et al., 2022
Fuzzy logic model (FLM) for optimization	The optimization model has reached three distinct sections: the supply chain, management of the operations, and the experience of seafood consumers	Zhang et al., 2023
The fuzzy-based Fish Swarm Algorithm (FSA) to solve the optimal design of nano-scale circuits	The method performed correctly in terms of „energy," „cost," „area" and „delay" where it surpassed others	Zhang and Zhang, 2022
The novel fuzzy adaptive jellyfish search-optimized stacking system (FAJS-SS) was integrated with the jellyfish search (JS) optimizer, the fuzzy adaptive (FA) logic controller, and the stacking ensemble ML	The FAJS-SS predicted more accurately than the other ML systems	Truong and Chou, 2022
The new fuzzy logic approach based on potentiometric measurements obtained with three different miniaturized chalcogenide glass sensors in various heavy metal solutions	The program's limitations, a comparison of computed and expected results for the sample composition as well as heavy metal ion concentration were demonstrated and addressed	Turek et al., 2009
Machine learning (ML) algorithms, ANFIS for identification of the algal bloom prediction	The adaptive neuro-fuzzy inference system (ANFIS) outperformed the other models examined due to its consistent and outperforming prediction	Ly et al., 2021
The Fuzzy Logic adjust (FLC) system adjusts the water temperature for maximum growth and quantity of produce	The water temperature was precisely adjusted to provide optimal growing conditions for the environmentally friendly and efficient production of freshwater and marine fish	Farghally et al., 2014

Journal of Food Safety and Food Quality 75, Heft 2 (2024), Seiten 35–64

by physical, microbiological, or biochemical changes. It is very essential to apply a wireless sensor network (WSN) monitoring system and knowledge engineering to monitor dynamic indicators that affect quality characteristics and to develop a knowledge-based HACCP quality control plan to enhance the quality of fishery products in the real cold-chain environment (Feng et al., 2019). Based on the notion of complete quality management, a service optimization model has been built with three distinct sections: the supply chain, management of the operations, and the experience of consumers. The systematic analysis leads to a thorough understanding of the difficulty, systematic nature, and timeliness of fresh product management operations (Zhang et al., 2023). Fishery products, which account for a significant share of the worldwide food supply, is extremely nourishing, perishable, and subject to pre-harvest and postmortem variables. Traditional approaches are time-consuming and labor-intensive, and they do not offer real-time or in-field applications in these fishery products monitoring for quality. Thus, novel uses of advanced instruments (gas sensors, electrochemical, colorimetric, machine learning (Saeed et al., 2022), and mathematical models have been essential (Kılınç et al., 2022a, Kılınç et al., 2022b). In the seafood industry, new product development is increasingly dependent on product line extension. These must be tailored to the needs of the customer and the retailer, and they must be available with short lead times. One way for seafood companies to handle this problem is to make use of the benefits and prospects of an IT-based approach to product modeling (Jonsdottir et al., 2000). Food products constitute a significant source of protein. Despite its usefulness, labeling knowledge was reported to be relatively limited for food safety. Therefore, a consumer method was investigated, which was based on a consistent fuzzy preference relation with the geometric Bonferroni mean. The study‘s findings not only contributed to the fishing and aquaculture business, but also the policy ramifications and future research investigations were explored (Cantillo et al., 2021). The current study proposed a model for assessing fish quality that relies on biogenic amine levels with the fuzzy logic model (FLM). Sardine (*Sardinella* sp.) was utilized in the study, and the generation of eight biogenic amines was tracked throughout fifteen days of storage at 10, 3, and 0 °C. Based on the findings, cadaverine, putrescine, and histamine were chosen as input variables for the FLM, while twelve quality ratings for fish quality were evaluated as variables that were output. The model‘s rules were applied to the input data, which was then defuzzified based on the output variables. Lastly, the developed model was used to assess fish quality, and Pearson correlation between storage durations and fish quality indicated r = 1, 0.95, and 0.97 for fish stored at 10, 3, and 0 °C, respectively (Zare and Ghazali, 2017). The difference in overall taste profile was detected by the electronic tongue, and the levels of free amino acids and 5’-Nucleotides were measured to investigate the taste quality of *Eriocheir sinensis* gonads after frozen storage in another study. The results demonstrated that the overall taste characteristic of samples could be effectively discriminated against using the fuzzy logic model during frozen storage (Fan et al., 2022). Another study aimed to improve an analog fish product with comparable nutrients using plant-based ingredients such as oyster mushroom, kombu and nori and rate them on a 9-point hedonic scale in terms of sensory characteristics such as aroma, appearance, taste, juiciness, and texture. Optimization using D-optimal mixture design and fuzzy analysis for developing of plant-based fish analog were performed (Patil et al., 2023).

Conclusion

Technology is developing day by day. With the developing technology, methods for determining quality by easy, fast, reliable, and cheap methods are preferred in all sectors, such as the food and marine food sectors. With the advancement of technology, methods for establishing quality that is simple, rapid, reliable, and inexpensive are sought in all industries, including the food and marine food sectors. It is preferable to combine one or more approaches to determine the quality and safety of food products. Thus, by determining the most appropriate method, the processing conditions, storage, optimizing settings for each food product, and so on, the effort of determining the most appropriate method continues at a rising rate. Fast techniques have many advantages over traditional methods in terms of usability in determining the quality and safety of foods. Furthermore, they also have significant advantages because they can be used in a variety of issues such as predicting the quality, shelf life, and risk evaluations of food products in mathematical models, which have become increasingly popular in recent years. Developing fast methods and the advantages of using constantly developing mathematical methods together with these methods in all sectors, especially food and marine food, will increase their preferences in the future as well as today. The fuzzy logic approach is one of these recommended mathematical methodologies. It is expected that upgraded versions of the fuzzy logic method will eventually replace the fuzzy logic versions currently in use.

Author statement

Berna Kılınç: content, design and writing the original draft, İrem Kılınç: content, design, writing the original draft, Çiğdem Takma: content, design, writing the original draft, Yakut Gevrekçi: content, design, writing the original draft

Conflicts of interest

The authors have no conflict of interests to declare

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