2024 VOLUME 3 ISSUE 2

FOOD BULLETIN

E-ISSN
2979-9848

PRENSIP

FOOD BULLETIN

2024 • VOLUME 3 • ISSUE 2

foodbulletin.net — foodbulletin@hotmail.com
prensip.gen.tr — info@prensip.gen.tr

Food Bulletin is a peer-reviewed scientific journal published by ***Prensip Publishing*** twice a year.

FOOD BULLETIN

2024 • VOLUME 3 • ISSUE 2

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http://foodbulletin.net

FOOD BULLETIN
e-ISSN: 2979-9848

https://prensip.gen.tr

RESEARCH ARTICLE

Determinants of Consumers' Willingness to Pay for Organically Produced Fluted Pumpkin (*Telfairia occidentalis*) among University Workers in Eastern Nigeria

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ARTICLE INFO

Article History
Received: 15.07.2024
Accepted: 25.12.2024
First Published: 30.12.2024

Keywords
Eastern Nigeria
Fluted pumpkin
Logit
Organic
Willingness to pay

ABSTRACT

As against conventional fluted pumpkin (*Telfairia occidentalis*), certified organic fluted pumpkin is safer, but the production and consumption are low. Awareness of heath benefit would likely spur the demand and stimulate production. Thus, this study examined the willingness to pay (WTP) for organically produced fluted pumpkin among the staff of Nnamdi Azikiwe University in Anambra State, Nigeria. Two-stage sampling procedure was used to collect data for this study. Four faculties with the largest staff population were purposively selected out of 14 faculties in the university, then, workers were selected proportionate to the population size of each faculty, resulting in a total sample size of 100. A structured questionnaire was used to collect data on consumers characteristics, awareness, willingness to pay and factors determining consumers WTP. Descriptive statistics and logit regression analysis were used to analyze the data. This study revealed that more than 70% of the respondents were aware of organic vegetables and about 67% of the respondents agreed that organically fluted pumpkin is healthier than conventionally one. On the average, up to 43.22 % of the respondents are willing to pay a premium for organically produced fluted pumpkin above (N200) the average cost of 200grammes of conventional fluted pumpkin. At 5% significance level of education (β=0. 81), and chemical consciousness (β=0.035) had positive influence on the willingness to pay while premium amount to be paid (β=-1. 1x 1005) and sex (β=-1.38), had negative influence. The study concluded that there was a potential market for organically produced fluted pumpkin among the university staff and recommended its prompt production.

Please cite this paper as follows:

Komolafe, J. O., Obiekwe, J. N., & Okechukwu, J. C. (2024). Determinants of consumers' willingness to pay for organically produced fluted pumpkin (*Telfairia occidentalis*) among university workers in Eastern Nigeria. *Food Bulletin*, *3*(2), 16-23. https://doi.org/10.61326/foodb.v3i2.275

1. Introduction

Organic vegetables, including fluted pumpkin, is gaining recognition among producers and consumers due to their benefits (Rahman et al., 2021). Producers of organic vegetables can tap into a rapidly growing market segment driven by health-conscious consumers seeking pesticide-free and environmentally friendly produce, allowing them to command premium prices and increase profitability (Reganold &

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Wachter, 2016). There are questions that has not been fully answered by researchers in Nigeria. These questions bother on health benefits, awareness associated with organically produced fluted pumpkin, its acceptability among consumers coupled with the pricing challenges (their willingness to pay a premium- WTPAP) faced by producers. There were three major factors identified in literatures that determine the willingness to pay (WTP) a premium for organic produce, these were demographic, economic, and risk attitudes toward human health and the environment (Amolegbe et al., 2022; Haghiri et al., 2009; Onyia et al., 2023). Researchers worldwide, uses mainly contingent valuation method to measure the WTP for a premium price for organic products (Haghiri et al., 2009; Onyia et al., 2023). The WTP a premium price and its determinants varies with products and locations therefore studies like this required.

Fluted pumpkin is a popular vegetable in Nigeria with great nutritional value (rich in vitamins A, C, and E, minerals such as calcium and iron, antioxidant) and medicinal qualities (boosting the immune system and reducing the risk of diseases like diabetes and hypertension) (Ojimelukwe & Philippa, 2022). Organic vegetables are free from synthetic pesticides and chemical residues, making them healthier options for consumers (Rahman et al., 2021). However, the extent to which consumers are aware of these health benefits and their impact on their purchasing decisions remains unclear. Understanding the level of awareness will provide insights into the potential demand for organically produced fluted pumpkin, the need for targeted educational campaigns and the requirements in enhancing the scope of production.

Awareness for organic vegetables measures the degree of consumers knowledge about the existence, benefits, and availability of organic vegetables. Empirical studies showed a growing awareness and demand for organically produced vegetables among consumers worldwide (Fernández-Rodríguez et al., 2019; Sánchez-Rodríguez et al., 2020). This trend is attributed to the increasing concerns about the negative health and environmental impacts of conventional vegetables (Gómez-Luciano et al., 2020).

Etuah et al. (2021) assess the level of awareness, perception and WTP for certified organic vegetables. The study discovered that 71% of the respondents had knowledge about organic vegetables and vegetable consumers were willing to pay between 31% and 51% premium for certified organic vegetables. Adams et al. (2018) in Ghana investigated the level of awareness and consumption of organic fluted pumpkin and found more than half (64.4%) of the respondents valued organic fluted pumpkin and were willing to pay up to 50% premium for it. The study showed price playing a key role in consumers' purchase intentions to organic fluted pumpkin. Iwu et al. (2020) estimated the awareness of organic fluted pumpkin among urban dwellers in Nigeria to be 83% of the respondents used for his research, but the consumption was relatively low, only 44% of the respondents consumed the vegetable in the past six months. Assessing the acceptability of organically produced fluted pumpkin among potential consumers influenced by factors such as income, taste, texture, appearance, and perceived qualities (Akinwehinmi et al., 2021; Bazhan et al., 2024) is important to ascertain the willingness of potential buyers embracing organically produced fluted pumpkin as against the conventional one. The knowledge of consumers' preferences and behaviour toward organic vegetables would shed light on the potential market size and consequently, solve the pricing challenges producers of organic vegetables are faced with in Nigeria. Organic production methods often incur higher production costs due to the implementation of sustainable farming practices and the abstinence from synthetic inputs (Reganold & Wachter, 2016). Consequently, organic vegetables are expected to command higher price to bridge price differential gap between organic and conventional. It is important to explore the impact of pricing by ascertain the WTP for organically produced fluted pumpkin and identify strategies that can enhance the affordability and accessibility of organic vegetables.

Consumer awareness of organic vegetables has witnessed a significant increase in recent years, studies have shown that consumer interest in organic agricultural practices and the associated benefits, such as reduced pesticide exposure and increased environmental sustainability, has grown in numerous nations (Nandi et al., 2016; Onyia et al., 2023). A survey conducted (Onyia et al., 2023) revealed that people are becoming more informed about the health benefits of organic vegetables and actively seek out organically produce vegetables. Similarly, Rahman et al. (2021) found that consumers were becoming more aware of the potential health benefits of consuming organic vegetables and were willing to pay a premium for them. This indicates a growing demand for sustainable and healthier food choices among consumers (Fernández-Rodríguez et al., 2019, Sánchez-Rodríguez et al., 2020). University staff was selected as a target population due to their level of education and presupposed level of awareness of the health benefits and the hazardous effect of conventional vegetables that are likely to be high in pesticides and chemicals from inorganic fertilizer

Research conducted by Cerda et al. (2012) suggests that customers are willing to pay a premium for organic vegetables. This study provides insights into customer preferences and their WTP for organic produce. It has been consistently shown that consumers perceive organic vegetables as being of higher quality, safer, and more ecologically friendly, leading them to place a higher value on such products. Factors such as age, income level, education, household size and awareness of organic agricultural processes influence consumers' WTP a premium price for organic products.

Since the organic vegetable market in Nigeria is still in its early stages, even though there are indications of growth and increasing interest among consumers. The empirical studies on consumers' WTP a premium for organic vegetables and its determinants in Nigeria are scanty**,** particularly among specific target groups like university staff (Smith & Johnson, 2021). Understanding the demand and market potential among the university staff will contribute to the development of tailored strategies for promoting organic vegetable consumption, especially among salary earners, and support the sustainable growth of organic vegetable production in Nigeria's agricultural sector. For as consumer awareness and demand for organic vegetables continue to rise, the organic farming sector in Nigeria is expected to expand in the future The findings can inform producers, policymakers, and stakeholders about the market potential and opportunities for investment.

The objectives of the study are:

1. Assess consumer's awareness of organic fluted pumpkin benefits.
2. Aassess the WTP for organically produced fluted pumpkin and;
3. Estimate the determinants of consumers' WTP for organically produced fluted pumpkin.

2. Materials and Methods

2.1. Conceptual Framework

The conceptual framework (Figure 1) shows how the concept of WTP involves several interconnected key variables that influence consumers' decisions regarding the purchase of the product. At the core of the framework is "Consumers' acceptance of the product," which plays a pivotal role in determining their WTP. If the target audience perceives the organically produced fluted pumpkin positively, their likelihood of buying it increases. Buying will is an important factor that influences WTP. If consumers have a strong desire to purchase the product, they may be more willing to pay a higher price for it.

Risk preference also influences WTP, as consumers who are more risk-averse may be less inclined to pay a premium for the product. Awareness of the benefits and characteristics of organically produced fluted pumpkin can positively impact consumers' WTP, especially if they understand the advantages over conventionally grown alternatives. Price sensitivity is another critical factor, as consumers with higher price sensitivity may be less willing to pay a higher price for organic products. On the other hand, if consumers are risk-tolerant, they may be more willing to pay a higher price for it.

Quality perception is vital as well, as consumers' perception of the quality and value of the organically produced fluted pumpkin will affect their WTP. Finally, socioeconomic characteristics of consumers, such as income level, education, and occupation, can influence their WTP for organic products, as individuals with higher socioeconomic status may be more inclined to prioritize health and environmental concerns. Overall, the interaction between these concepts shapes the WTP for organically produced fluted pumpkin targeted consumers.

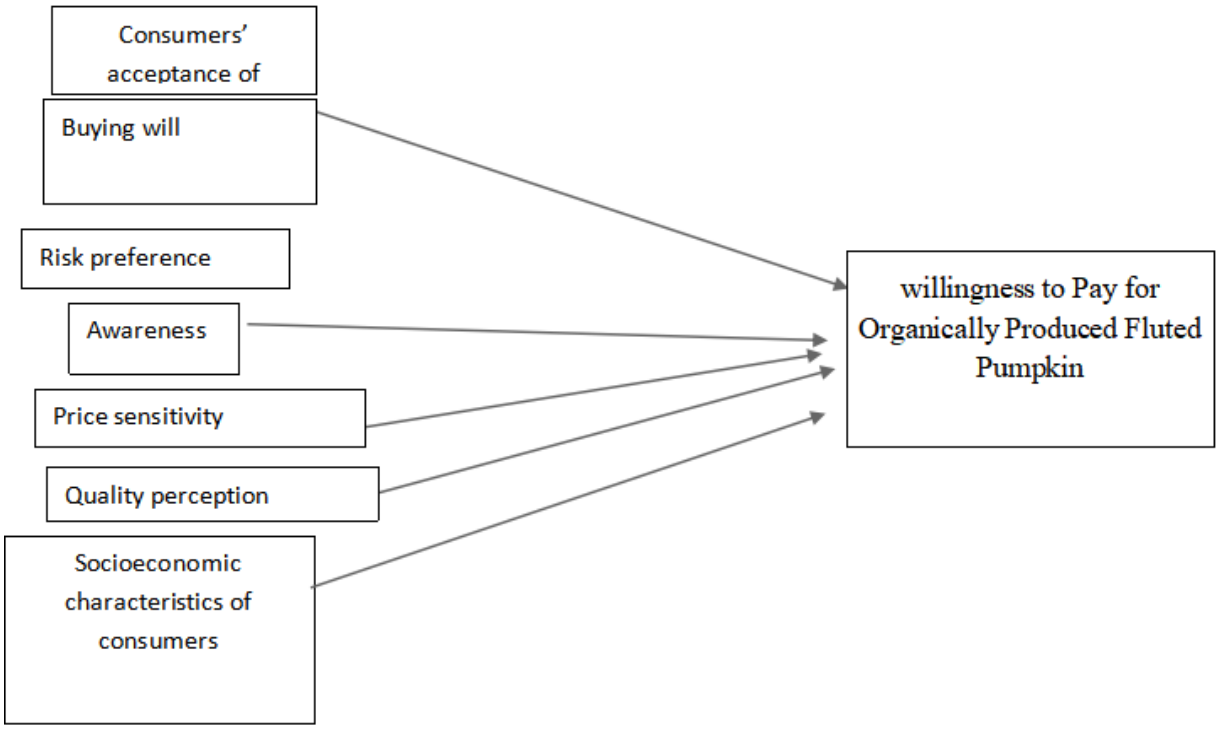

Figure 1. Conceptual framework, adapted from Osadebamwen et al. (2015) and modified.

2.2. Theoretical Framework of Contingent Valuation Approach

This study adopted contingent valuation approach (CVA) for the survey which is a popular methodological approach among researchers studying WTP for goods or services (Chuen-Khee & Othman, 2010; Nandi et al., 2016; Sriwaranun et al., 2015). Contingent valuation method is a preference method used in valuing positive externality (Carson et al., 2003; Onyia et al., 2023) Contingent valuation enables direct estimation of WTP for a product. Respondents were asked questions on how much they would be willing to pay for perceived benefits of a product or service in a typical market situation (Nandi et al., 2016). Thus, to apply contingent valuation approach, hypothetical market was created for the product or service under study. It is a reliable methodology used to collect information (Arrow et al., 1993). The approaches normally use were: Open-ended question, iterative bidding, dichotomous choice and payment card approach (Bhattarai et al., 2017). Common methods in dichotomous choice *Contingent Valuation* approach could be single-bounded and double-bounded methods. This study used single-bounded *Contingent Valuation* approach, where respondents were asked whether they are willing to pay ahigh amount for a product and for a yes response, follow-up question was asked for the ceiling amount they are willing to pay, conversely, for a 'no' response, follow-up question was that what amount of money they are willing to pay for the product under evaluated (Bhattarai et al., 2017). Contingent valuation information is then modeled as below (Alberini, 1995):

WTP is $Wi* = Xi\ \alpha + \varepsilon i$ (1)

Where, $Wi*$ is WTP (Yes/ No), (2)

ε is the error term with zero-mean, and vector Xi is the respondent characteristics.

The model for the observables expresses the likelihood of respondent agreeing to a given proposed amount and the individual characteristics. That probability is $Pr\ (Wi* \geq Oi|Xi)=1-G(Oi|Xi)$, where Oi is the price offer G is distribution function of $Wi*$, $Wi*$ is assumed to be normal or logistic. The probability of "yes" to a payment of Naira C is $Pr(W*=1)=E(W*)=Pr(Wi*\geq Oi)=1-F((Oi-Xi\beta)/\sigma)$, where $Wi*$ equal to one if respondent accepts the offer Oi (and zero otherwise), F is the distribution function of ε/σ , and σ is scale parameter of distribution of $W*$ The probability of declining to pay proposed amount is $Pr(W*\leq Ci) = F((Oi-Xi\ \alpha)/\sigma)$.

2.3. Logit Model

To estimate the determinants of consumers' WTPAP price for organic fluted pumpkin the relationship between independent variables and WTP was analyzed using the Logit Model. Logit regression models relationships between a dichotomous response variable and a set of regressor variables. Assuming the probability that consumers' WTPAP price for organic fluted pumpkin is equal to proportion of consumers' WTPAP price, then the individual empirical models to be estimated may be specified as:

$$WTP = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \quad \ldots \alpha_n X_n + \varepsilon_i \ \ldots \quad (3)$$

$$NWTP = \delta_0 + \delta_1 X_1 + \delta_2 X_2 + \quad \ldots \gamma_n X_n + \varepsilon_i \quad (4)$$

Where;

WTP=consumers' WTPAP price for organic fluted pumpkin

NWTP=consumers' no WTPAP price for organic fluted pumpkin

α and δ were parameters to be estimated.

X_i= were explanatory variables.

ε_i = error terms

The Explanatory Variables include:

X_1 = Years of formal education (years); X_2 = Age (years); X_3 = Gender (Male = 1 female = 0); X_4 = Household size; X_5 = Marital status (Married = 1 otherwise = 0); X_6 = Perceived Health Benefits of Organic Produce; X_7= Income Level (N); X_8 = Awareness of Organic Farming Practices; X_9 = Environmental Concerns.

2.4. Area of the Study

The study was carried out in Southeast, Nigeria. Southeast, Nigeria consists of five states: Ebonyi Abia, Anambra, Enugu and Imo. The zone is surrounded in the West by Delta and Edo States, in the East by Awka Ibom and cross River States, in the North by Kogi and Benue States, and in the South by Bayelsa and Rivers States. The area is inhabited by the Ibo people and their native language is Igbo, though pidgin English is widely spoken and English is the official language. The zone lies between latitude 40 longitude 60 401E and 80 301E. and 501N to 70 10°N.The area of land covered by the zone is 26,982.67 km^2 which is 8.5% of the total land area in Nigeria. they have a total population of 16,395,555 million according to National Population Commission, 2006. The zone has five federal universities namely University of Nigeria, Nsukka, Nnamdi Azikiwe University, Awka, Federal University of Technology, Owerri, Michael Okpara University of Agriculture, Umudike, Federal University, Ndufu-Alike Ikwo.

2.5. Sample Technique and Sample Size

This study used primary data that were collected using well-structured open-ended questionnaire. Data collected were university workers' demographic, economic, and risk attitudes toward human health and the environment. The study adopted a three-stage procedure for its sampling. In the first stage two Federal Universities in Southeastern Nigeria were selected purposefully. These were Nnamdi Azikiwe University, Awka,

and Federal University of Technology, Owerri. Second stage involved stratified each university by their faculties and purposive selection of faculties with the largest population of workers was done and in the third stage workers were selected proportionate to the population size. The total number of respondents selected were two hundred workers.

3. Results and Discussion

The respondents were asked question on whether they had aware of organically fluted pumpkin vegetable. Table 1 showed that all the respondents were aware/ heard about organic vegetables. This corroborates the work of De Zoysa and Waisundara (2022). Concerning its availability in the market, 20.00 percent of the respondents asserted that it is available, 60.00 percent asserted that it is not easy to come by, while the remaining 20.00 percent responded were indifferent. All the respondents (100%) were well informed about the benefits of organically fluted pumpkin. About sixty seven percent of the respondents agreed that organically fluted pumpkin is healthier than conventionally one, while (30.00%) were indifferent and only (3.00%) disagreed. About seventy-six percent of the respondents were highly concern about chemicals in food crops. (16.00%) of the respondents were mildly concerned, (11.00%) were indifferent and (3.00%) felt unconcern.

Table 1. Awareness of organic fluted pumpkin benefits (OPFP).

Variables	Frequency	Percentage
Information about availability of OPFP in the market		
1. Yes	40	20.00
2. No	120	60.00
3. Indifferent	40	20.00
Awareness of OPFP health benefits over convention		
1. Yes	200	100.00
2. No	0.00	0.00
Level of agreement that OPFP is healthier than conventionally on		
1. Strongly agree	60	30.00
2. Agree	74	37.00
3. Neutral	60	30.00
4. Disagree	6	3.00
Concerned about chemicals in foods		
1. Very concerned	140	70.00
2. Somewhat concerned	32	16.00
3. Neutral	22	11.00
4. Not very concerned	6	3.00

Table 2 showed that only (43.00 %) of the respondents are willing to pay a premium for organically produced fluted pumpkin. Thirty seven percent of the respondents were willing to pay additional 20% on the market price of the conventional one, (28.00%) of the respondents were willing to pay additional 10% on the market price of the conventional, (20.00%) were willing to pay extra 30% while, the remaining (15.00%) were willing to pay extra premium above 30%. Factors motivating respondents' WTPAP for OPFP were identified to be better health benefits (70.00%), environmental concerns (10.00%), support for local farmers (7.00%) higher quality and taste (12.00 %) and other reasons (2.00%). Frequency consumption of fluted pumpkin was presented in table 3.4 as once a week (50.00%) 2-3 times a week (40.00%) 4-5 times a week (22.00%), and > 5 times a week (13.00%). The Present purchase channels of fluted pumpkin were presented as follows: local market (69.00%), supermarket (14.00%), online retailer/home delivery (2.00%) and. farm gate (15.00%).

Table 3 presented the result of logit model used to investigate the determinants of university staff WTP for organically produced fluted pumpkin. Nine variables were included in the model, only four of the variables were significant at 5%. The likelihood ratio chi-square of 63.317121 with a p-value of 0.000 and Pseudo $R^2 = 0.1823$ reveals that the whole was statistically significant at 1% level of significance.

Table 2. WTP for organically produced fluted pumpkin (OPFP).

Variables	Frequency	Percentage
Willing to pay a premium for OPFP		
1. Yes	86	43.00
2. No	114	57.00
Maximum premium willing to pay for OPFP		
1. 10%	56	28.00
2. 20%	74	37.00
3. 30%	40	20.00
4. 40%	14	7.00
5. ≥ 50%	16	8.00
Factors motivating premium pay for OPFP		
1. Better health benefits	140	70.00
2. Environmental concerns	22	11.00
3. Support for local farmers	10	5.00
4. Higher quality and taste	24	12.00
5. Other	4	2.00
Frequency consumption of fluted pumpkin		
1. Once a week	50	50.00
2. 2-3 times a week	80	40.00
3. 4-5 times a week	44	22.00
4. > 5 times a week	26	13.00
Present purchase channel for fluted pumpkin		
1. Local market	138	69.00
2. Supermarket	28	14.00
3. Online retailer/home delivery	4	2.00
4. Farm gate	30	15.00
Is there a price difference between organic and conventional products is justified?		
1. Yes, definitely	66	33.00
2. Yes, to some extent	54	27.00
3. Not sure	48	24.00
4. No	32	16.00

Table 3. Determinants of WTP for organically produced fluted pumpkin (logit regression result).

Logit Regression Result			**Marginal effect**	
Variables	**Coefficient**	**P>|z|**	**Coefficient**	**P>|z|**
Age	-0.0594041*	0.042	-0.0146838 *	0.042
Gender	-1.377026 **	0.008	0.320928 **	0.003
Marital status	0.2419634 *	0.037	0.0598096 *	0.216
Household size	-0.001	0.994	0.0003	0.994
Years of education	0. 809**	0.001	0.047**	0.004
Monthly income	-3.79e-07	0.966	-9.36e-08	0.966
Premium percentage	-1. 1E- 05**	0.003	-5.4E-02**	0.0010
Health consciousness	0.105*	0.064	0.026*	0.073
Chemical in vegetable conciseness	0.035**	0. 007	0.003**	0.0041
Constant	0.4712649	0.832		
Log likelihood = -63.317121	Prob > chi2 = 0.0100	LR chi2(9) = 101.3	Pseudo R^2 = 0.1823	Number of obs = 200

**5% significant level; *10% significant level.

Years of education positively and significantly contributed to the determinants of university staff WTPAP for organically produced fluted pumpkin. This implies that with one year increase in the years spent in school there is likelihood that respondents will choose improved maize seed. The marginal effect (0.05) shows that with one year increase in year spent in school respondents has the likelihood of increasing their WTPAP by 5% ceteris paribus. This is in line with the work of Katt and Meixner (2020) and Magnusson and Cranfield (2005) that report a positive relationship between education and the WTPAP for organic food products, but at variance with the work of Haghiri et al. (2009).

Gender negatively affects WTPAP and it is significant at 5%. The marginal effect (0.33) shows that being a female have the likelihood of decreasing the WTPAP by 5% ceteris paribus.

Percentage of premium to be paid has negative and significant effect on WTPAP. The marginal effect (-5.4E-02) showed that the WTPAP decreased by 0.5%. Consciousness of chemical in vegetable has positive effect on WTPAP. This implies that as the consciousness of chemical in vegetable increases there is likelihood that farmers will choose to pay a premium. The marginal effect (0.003) shows that with an increase in the consciousness of chemical in vegetable by respondent there is likelihood that they will be willing to increase the premium paid by 5 %. Marital status and health consciousness were positively related to the premium paid by respondent and were significant at 10 %, but age was negatively related to the premium paid by respondent and were significant at 10 %.

Therefore, this outcome permits the rejection of earlier stated null hypothesis that University staff willingness was not to pay for organically produced fluted pumpkin; hence the alternative hypothesis is accepted.

4. Conclusion

The study provides empirical evidence of the University staff WTPAP for organically produced fluted pumpkin. University staff are willing to pay a higher premium for organically fluted pumpkin above the N200 they pay for N200grammes of conventional one. They are well informed about the benefits of organic fluted pumpkin and noted that it is healthier. Gender negatively affects WTPAP, while education, marital status and health consciousness positively influenced the premium payment

5. Recommendations

Based on the finding of this study the following policy recommendations were made:

- Due to low level of awareness and the level of significance of education, workshops and seminars needed to be conducted by food safety organizations like NAFDAC to sensitized consumers on the need to embrace organic products.
- From the study male were ready to pay higher premium therefore, women should be enlightened about the dangers of chemicals in food and be encouraged to be ready to pay premium on organic products.
- Consciousness of the hazard of chemicals in food was significant in payment of premium, therefore, people should be sensitized about the hazards of consuming conventional vegetable that were treated with chemicals.

Conflict of Interest

The authors declare no conflict of interest.

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http://foodbulletin.net

FOOD BULLETIN
e-ISSN: 2979-9848

https://prensip.gen.tr

RESEARCH ARTICLE

Identification of Food Safety Intervention Points by Application of Social Practice Theory: Case Study of Pushcart Foods

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ARTICLE INFO

Article History
Received: 21.09.2024
Accepted: 25.12.2024
First Published: 30.12.2024

Keywords
Aerosols
Coliform bacteria
Food safety
Pushcart street food
Salmonella
Social practice theory

ABSTRACT

The applicability of the sociological theory of social practice (SPT) for locating safety intervention points in street food practices was investigated. A randomly selected 100 pushcart street foods/vendors were used for the study. The practice elements enunciated in the social practice theory (materials, competence, social meaning) were identified in pushcart practices by non-participant observation and structured questionnaire. Warmer/containers, plates, dishing spoons, wash-water and food were identified as practice materials. The observed practices bothering on competence were: washing and re-use of plates, opening and closing of food containers, exposure of dishing spoons, use of non-potable wash water and environment of sales points. In order to confirm intervention points indicated by these practices, the presence of coliforms and *Salmonella* on the elements and sales points (Motor Parks, markets, workshops, construction sites) aerosols were investigated. Coliforms and *Salmonella* were isolated from the material elements in 16-64% of the pushcarts barely 4 hours after commencement of sales. The choice of sales points was influenced by satisfactory income (meaning element) despite their poor sanitary conditions. The high levels of aerosolised coliforms (2.29-3.38 log cfu/m^3) in these sales points indicated environment as an intervention point. This was corroborated by the association between coliform levels on the material elements and the environment (X^2=6.32-19.46; P=0.000-0.042). In conclusion, competence and sales environment were indicated as intervention points for pushcart food safety as supported by microbiological analyses. Thus, intervention by encouraging sales of packaged foods in pushcarts can eliminate incompetent handling, vulnerable practice materials and exposure in unsanitary environment.

Please cite this paper as follows:

Ejechi, B. O., & Ejechi, E. O. (2024). Identification of food safety intervention points by application of social practice theory: Case study of pushcart foods. *Food Bulletin*, *3*(2), 24-33. https://doi.org/10.61326/foodb.v3i2.289

1. Introduction

Street foods are common in urban areas of Nigeria as well as in many developing countries. Hawkers or vendors and food stalls constitute the street food system. The foods are sold on the streets or public places like Motor Parks, markets, construction sites and mechanic/furniture workshops. They are mostly inexpensive hence they attract a lot of patronage. However, several reports have raised concerns on the issue of safety due to food-borne diseases associated with street foods (e.g., Desye et al., 2023; Lawal et al., 2014; Ma et al., 2019; Mazi et al., 2023; Nkosi & Tabit, 2021; Okojie & Isah, 2014; Ossai, 2012). The concerns bothered on poor hygiene and sanitation, handling, exposure of food on the streets and lack of basic training on food safety measures.

The concern for the safety of street foods due to its association with high prevalence of food-borne diseases (Tuglo et al., 2021) has led to attempts at setting hygiene rules for street foods (Bamu, 2019). These rules have always been difficult to enforce. A forcible ejection from the streets (López-García,

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2017) is most likely to always fail because the vendors are mobile and would always return. Besides, street food vendors constitute part of the informal economic sector that should not be eliminated. Thus, the difficulties associated with changing the behaviour of the street food vendors necessitated the need to consider other options for limiting the health risks associated with street foods. The social practice theory (SPT) may provide an alternative approach because it focuses on the "action" of the individual and not the individual.

Practice has been described as a multitude or line-up of human activities performed on routine or daily basis (e.g. household works, smoking, drinking, and income generating activities) that may be mutually dependent and commonly undertaken in the society (Holtz, 2014; Schatzki, 1996). These routine practices have been put together to form SPT by several workers beginning with Bourdieu (1977) and Giddens (1984). Succinctly, Reckwitz (2002), Shove et al. (2012), Holtz (2014), and Maller (2015) described social practice as an entity composed of three interconnected elements; competence or know-how, social meaning and materials. Social meaning involves motivation and the aim of the practice, know-how or competence implies practical knowledge of the protocol or procedure to carry out the practice while materials are the tools and equipment involved in the practice (Heidenstrøm, 2022). Studies of social practice are based on these elements as it occurs and interwoven in the specific practice or actions of the individuals and not on the individual (actors). The task before researchers would therefore be to identify the elements in the practices that are vulnerable to hazards for the purpose of intervention.

SPT researchers have mainly focused on public health especially health risk behaviour such as smoking, alcohol use, diet, physical activity, sexual behaviours, physician visits, medication adherence, screening and vaccination (Conner & Norman, 2017). Meier et al. (2018) posited: "in contrast to the heavily resourced science investigating individual behaviour, practice theory offers an alternative framing that recognizes the importance of fellow human beings, material objects, the affordances of equipment, infrastructural settings, spatial layouts of contexts or the temporal sequences which steer performances of practice". Thus it provides the framework for interventions by targeting the elements for changes, re-arrangement and modification or disruption of the connections between elements. The take home from this brief overview of SPT is that targeting the elements and their interplays for intervention can ultimately and potentially lead to health and safety benefits. Although SPT has been applied in some investigations on food safety, (Ejechi & Ejechi, 2020; Ejechi et al., 2023) it is yet to be fully extended to other food services like pushcart street foods.

Pushcart foods are usually prepared at home and sold at stoppage points along streets or pushed to markets, Motor Parks, workshops, construction sites and schools. The "journey direction" of the pushcarts is usually influenced by patronage hence some of the final sales-points may be located in poor sanitary environment where customers are plentiful. The material elements of the pushcart practices may therefore be exposed to contamination; and this may be worsened if the interconnecting competence and meaning elements do not forestall the exposure of the material elements to contaminants. It is therefore necessary to use SPT to identify practices that expose pushcart foods to contamination and how they are interconnected. The vulnerable practices(s) would be subsequently tested for microbial contamination for confirmation as potential intervention points. The study was therefore designed to ascertain the potential of the "material, competence and meaning practice elements" enunciated by SPT, to locate intervention points for ensuring the safety of pushcart street foods.

2. Materials and Methods

2.1. Selection of Pushcart Food Vendors

Although pushcarts move along the streets in neighbourhoods, it is easier to find them in four major locations (motor parks, markets, workshops and construction sites). Thus 5 pushcarts from each of the 4 major sales points were randomly selected from 5 major towns (Asaba, Agbor, Ughelli, Warri and Sapele) in Delta State, Nigeria. This brought the total numbers of pushcart that were studied to 100. Background characteristics of the pushcart vendors such as age, gender and education were obtained via one-on-one interview by trained research assistants after obtaining their verbal informed consents.

2.2. Identification of Practice Elements in Pushcart Services

The surveillance method of non-participation observation was adopted for identifying the material elements and competence in pushcart food service practices. Competence elements included hygienic handling of food and sales materials (plates, dishing spoons, wash water, warmer/food containers, and cutleries) and the sanitary condition of their major sales points. They were assessed by visual observation. The assessment of sanitary environment was based on: presence of waste dumpsites; blocked drainages; and dusty environment within 50m radius of the sale points. Hygienic handling competence was confirmed by the counts of total coliform bacteria and the presence of *Salmonella*. in food and on material elements. The assessment of the meaning element was based on the frequency of patronage by customers (sometimes/most of the time) and pushcart vendors' income generation (satisfactory/not satisfactory).

2.3. Determination of Total Coliform Bacteria and Presence of *Salmonella*

For the purpose of indicating the presence and source(s) of contaminants, laboratory tests for coliform bacteria in food, plates, spoons, drinking water and wash-water were conducted. Preliminary observation had showed that rice was sold by all pushcarts, which indicated its popularity hence it was used to test vulnerability of pushcart food to contamination. The rice meal was purchased after preparation or before sales commenced and later after 2 and 4 hours of sales and subsequently tested for coliform counts. The swab/rinse method with MacConkey agar (MA) was used to enumerate coliforms on the surfaces of plates, dishing spoons and cutleries following oral permissions granted by the vendors. Unused plates and plates washed for re-use were swabbed. The above procedure was repeated with respect to the detection of *Salmonella* using Bismuth Sulphite agar medium. Airborne coliform bacteria in the sales locations were enumerated by the settling plate technique where MA plates were exposed on a table at 1m above the ground for one hour. The Millipore membrane (0.20 µm pore) filter method on MA was used for the enumeration of coliforms in the wash water. All plates were incubated for 24-48 hours at room temperature (30±2°C) before the colonies that appeared were counted (coliforms) while *Salmonella* was recorded as either present or absent.

2.4. Data Analyses

The relationship between coliform counts in pushcarts rice meal, wash-water or plates and the sanitary condition of the sales points (within vicinity of dumpsites, drainages and dusty environment) was analysed with chi square statistics (SPSS version 21). Standard total coliform counts' permissible limits ($\leq$10 cfu/g/cm^2/100ml) was used to analyse the safety status of the food and material elements based on a dichotomy of below/above permissible limits. The Omeliansky formula (Awad & Mawla, 2012) was used to compute the population of the airborne coliforms ($N = 5a \times 10^4 (bt)^{-1}$ where: N = cfu/m^3; a = number of colonies/plate; b = dish square cm; t = exposure time in minutes).

3. Results

The pushcart vendors were entirely females and were mainly 31-50 years in age (Table 1). None of them had tertiary education while less than 15% had no education (Table 1). Vendors with primary education were slightly more than those who attended secondary schools (Table 1). The materials associated with the pushcart food services and food types are presented in Table 2.

Table 1. Socio-demographic characteristics of pushcart street food vendors.

Variables		***N*=100**	**%**
Gender	Male	0	0.0
	Female	100	100
Age	20-30	17	17
	31-40	42	42
	41-50	31	31
	>50	10	10
Education	None	12	12
	Primary	48	48
	Secondary	40	40
	Tertiary	0	0.0

Table 2. Identified material elements used by pushcart vendors based on non-participatory observation.

Food service activities	**No of Pushcarts involved (*N*=100)**		
		n	**%**
Drinking water source	From pushcart	66	66
	Nearby shops	34	34
Types of drinking water	Sachets	96	96
	Bottles	4	4
Water for washing plates and cutleries	None	23	23
	Carried in pushcart	43	43
Type of service	From nearby taps at sales point	34	34
	Take-away packs	17	17
Types of food sold	Pushcart plates/cutleries	83	83
	Customers' plates/cutleries	25	25
	Rice	100	100
	Beans	85	85
	Moimoin (bean pudding),	70	70
	Fried plantain,	67	67
	Yam	58	58
Keeping food warm with:	Warmer containers	82	76
	Stove (gas, kerosene, coal)	08	08
	None	10	16

Majority of the pushcarts carried drinking water which was mainly from sachets (Table 2). Water for washing plates and cutleries were either carried in the pushcarts or were obtained from nearby bore holes (Table 2). The table further showed that most of the pushcart vendors serve food with their own plates while a markedly lower number of customers came to purchase food with their own plates. Sales with take-away packs were minimal (Table 2). Maintaining food warmth with warmers was markedly more frequent than using portable stoves while a negligible number of pushcarts had no means of keeping food warm (Table2). Although the food types sold varied, all the pushcarts sold rice (Table 2).

The indication of competence in food services is presented in Table 3, which shows that the prevalence of poor hygienic handling of plates, dishing spoons and manner of dishing food was above 70%. In addition, the use of hand gloves was minimal while borehole water was mostly used for washing plates (Table 3). The pushcart food business was meaningful to the vendors because patronage was markedly more of "most of the time" and most of them reported satisfactory income generation (Table 3). As shown in Table 4, more than half of the pushcarts in the markets and Motor Parks were in the vicinity of waste dumpsites while those in workshops and construction sites were mainly in dusty environments; only few of them were close to blocked drainage channels.

Figure 1 presents the variations of the coliform counts in rice meals tested after 2 and 4 hours sales period by sales environment. The coliform counts at 2 hours were generally low irrespective of the sales environment of the pushcarts. However, no coliform bacteria were found in the rice meals of more than half of the pushcarts at 2 hours (Figure 1). All the pushcart rice meals in the Motor Park environment were contaminated by coliforms after 4 hours of sales while 80-96% (20-24/25) of the pushcarts in the other sales environments had contaminations at varying levels (Figure 1).

Table 3. Indicators of meaning and competence elements based on respondents' responses and pushcart vendors' habits.

Practice indicators	Response options	*N*	Prevalence	
			n	**%**
Meaning elements		140*		
Patronage of pushcart food	Sometimes		51	36.4
	Most of the time		89	63.6
*Vendor income generation	Satisfactory		67	57.1
	Not satisfactory		33	42.9
Competence elements	NA	100**		
Washing/re-use of plates/cutleries	NA		86	86
Opening and closing of food containers	NA		83	83
Exposure of dishing spoons	NA		74	74
Use of tap/borehole water for washings	NA		78	78
Use of hand gloves	NA		11	11

*Respondents; **Pushcarts; NA, not applicable.

Table 4. Sanitary condition of the major sales points within 50m radius of pushcarts.

Sales points	No of pushcarts [n(%)] within:		
	Dusty environment	**Dumpsites vicinity**	**Blocked drainage area**
Markets (*N*=25)	9(36.0)	13(52.0)	3(12.0)
Workshops (*N*=25)	15(60.0)	6(25.0)	4(16.0)
Construction sites (*N*=25)	18(72.0)	5(20.0)	2(8.0)
Motor Park (*N*=25)	6(25.0)	14(56.0)	5(20.0)

A further analysis of the varying levels of coliform counts in the rice meals is presented in Table 5. Coliform counts below the permissible limit were encountered in almost all pushcart rice meals sold 2 hours after cooking while 16-64% of the pushcarts had counts above the limit after 4 hours (Table 5). Motor Parks had the highest number of pushcarts having rice meals with non-permissible coliform counts (Table 5).

Non-permissible coliform counts were found more in washed and re-used plates than in unused plates and it tended to be greater in Motor Park environment (Table 5). Wash-water followed the same trend with the highest in Motor Park-based pushcarts. The drinking sachet water were generally free of coliform bacteria hence it was not included in the table. *Salmonella* was detected only in rice meals sold after 4 hours and in 12.0-48.0% of the pushcarts (Table 5).

Salmonella was also detected in washed and re-used plates and wash water, but not in unused plates (Table 5). The analysis in Table 6 shows that the presence of coliform bacteria in rice meal, wash-water and washed plates except unused plates, were significantly associated with the sales environment. High

airborne coliform bacteria counts with greater population in Motor Parks and markets were encountered in the sales environments (Figure 2).

Table 5. Prevalence of pushcarts with material elements containing coliform bacteria counts below or above permissible levels and the presence of *Salmonella* as indicators of hygienic practices.

Pushcart services		**No of pushcarts involved**		
Location of pushcarts (*N*=25/location)	**Material elements**	**Coliform limit***		***Salmonella***
		Above	**Below**	
		***n*(%)**	***n*(%)**	***n*(%)**
Market	Rice[a]	0(0.0)	25(100)	0(0.0)
	Rice[b]	10(40.0)	15(60.0)	7(28)
	Plates[c]	5(20.0)	15(60.0)	0(0.0)
	Plates[d]	10(40.0)	20(80.0)	10(40.0)
	Wash water	5(20.0)	25(100)	3(12.0)
Motor Park	Rice[a]	0(0.0)	25(100)	0(0.0)
	Rice[b]	16(64.0)	9(36.0)	12(48.0)
	Plates[c]	6(24.0)	19(76.0)	0(0.0)
	Plates[d]	14(56.0)	11(44.0)	11(44.0)
	Wash water	18(72.0)	7(28.0)	7(28.0)
Workshops	Rice[a]	0(0.0)	25(100)	0(0.0)
	Rice[b]	9(36.0)	16(64.0)	3(12.0)
	Plates[c]	2(8.0)	23(92.0)	0(0.0)
	Plates[d]	11(44.0)	14(56.0)	4(16.0)
	Wash water	10(40.0)	15(60.0)	5(20.0)
Construction site	Rice[a]	0(0.0)	25(100)	0(0.0)
	Rice[b]	4(16.0)	21(84.0)	3(12.0)
	Plates[c]	6(24.0)	19(76.0)	0(0.0)
	Plates[d]	10(40.0)	15(60.0)	6(24.0)
	Wash water	8(32.0)	17(68.0)	9(36.0)

[a]2 hours, [b]4 hours after cooking; [c]unused plates, [d]washed and re-used. *Total coliform permissible limit=10 cfu/g/cm^2/100ml.

Table 6. Chi square analysis of the association between coliform bacteria counts in pushcart rice meal, wash water or plates and the sales environment.

Occurrence of Total coliforms		**Pushcarts (*N*=100) in sales environment**				
Source	**Permissible limit**	***vicinity of dumpsites (*n*=48)**	***vicinity of drainage (*n*=38)**	**dusty area (*n*=14)**	**X^2**	***P***
Rice meal	Above	30	15	10	6.319	0.042
	Below	18	23	04		
Wash water	Above	24	10	12	15.126	0.001
	Below	24	28	02		
Unused plates	Above	20	12	04	0.951	0.622
	Below	28	26	06		
Washed plates	Above	31	10	12	19.463	0.000
	Below	17	28	02		

*50m radius.

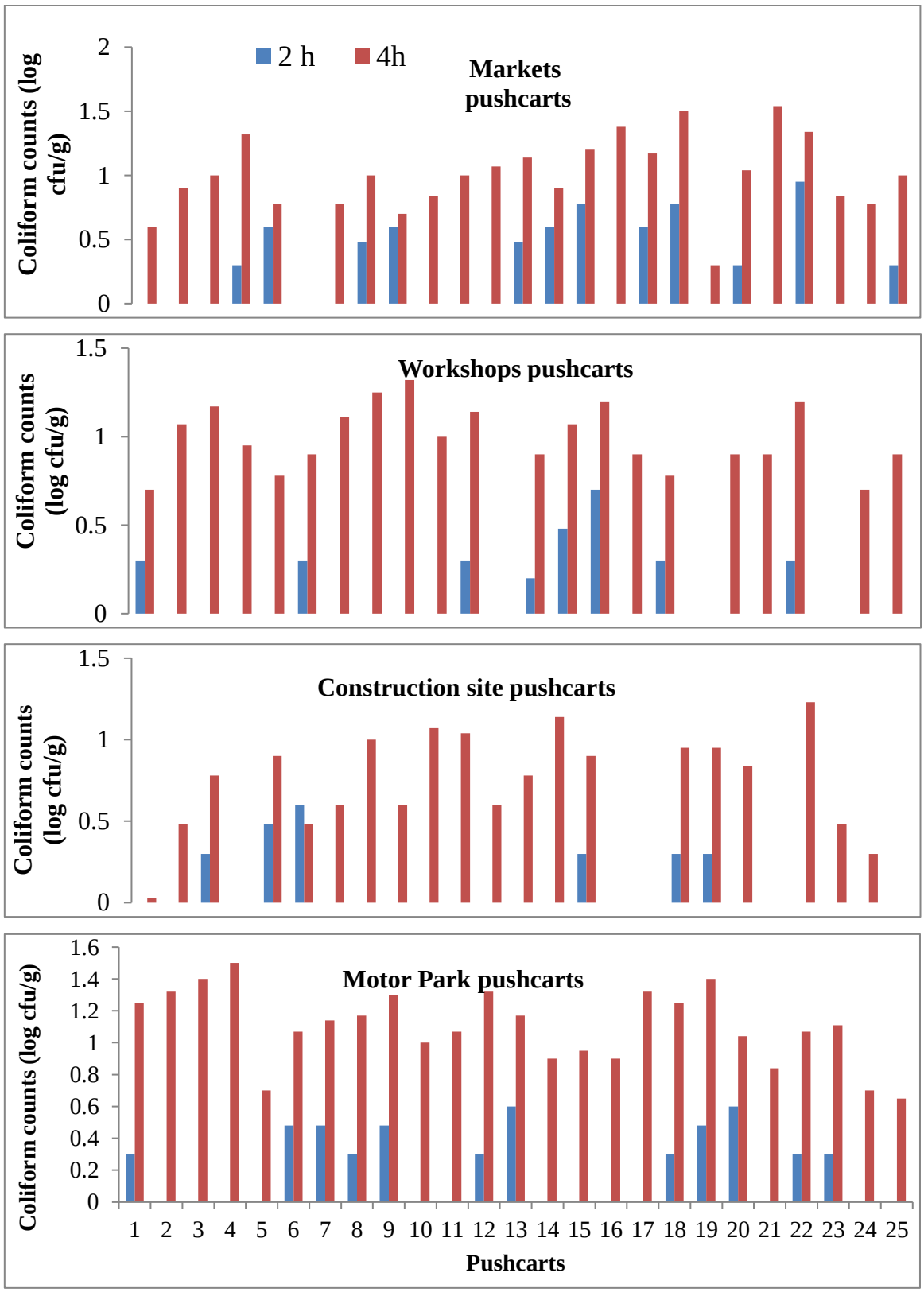

Figure 1. Trends in coliform bacterial population found in pushcarts' rice meals sold 2 and 4 hours after cooking.

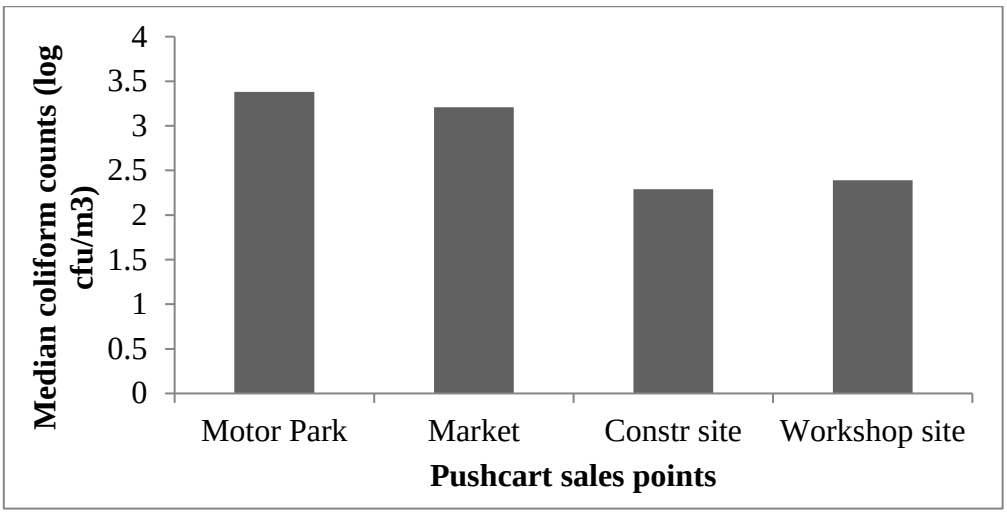

Figure 2. The population of coliform bacteria found in the air at pushcarts major sales points.

4. Discussion

The results revealed that the pushcart food practices involve material elements that are exposed to contamination as confirmed by the presence of coliform bacteria and *Salmonella*. While the presence of non-permissible levels of coliform bacteria is a danger signal, the detection of *Salmonella*, a causative agent of typhoid fever, indicates potential transmission of food-borne diseases. It is known that unhygienic practices are common with street food vendors (Desye et al., 2023). The pushcart vendors were no exceptions hence their habits of exposing food via intermittent opening and closing of warmers, use of exposed plates and dishing spoons, and the use of non-potable wash-water were not surprising. These incompetent actions therefore become potential areas for intervention as envisioned by SPT. The case for intervention at the competence level is further promoted by the dominance of women with low education in the pushcart food business. Their understanding of health-related issues is limited (Feinstein et al., 2006; Mamady, 2016) and this will make it difficult to change their handling habits especially when patronage and income are substantial. In addition, the personal hygiene of pushcart vendors cannot be easily targeted for intervention because of the low level education. There is also evidence that food handlers tend to report adherence to hygienic rules whereas they do not most of the time (Mazengia et al., 2015). Thus the available options are either to remove the implicated material elements, modify or substitute them in accordance with the vision of SPT (Meier et al., 2018).

The sanitary conditions of the sales points were generally poor as the results showed. Human traffic and wind can aerosolise microorganisms from the soil and dumpsites and the microorganisms can ultimately reach or settle on the material elements. This inference is substantiated by the high counts of airborne coliforms encountered in the sales environment. This deduction is also supported by the finding that the levels of coliform bacteria counts on the material elements were significantly associated with the sales environment. Further evidence of the involvement of airborne bacteria in the contamination of the pushcart materials comes from the finding that either few or no coliforms were present in rice meal samples until 4 hours into sales. Thus, the interconnection between the material elements and competence extends to the sales environment.

From the totality of the findings and the foregoing discussion, it is obvious that the points for intervention lie mainly in the use and handling of plates, dishing spoons and wash-water (material and competence elements) and sales environment (social meaning elements). This deduction is consistent with the expectations of SPT framework. SPT focuses on the actions of the individual and by this the pushcart vendors' practice interconnecting sequences become targets for intervention. This is also in line with SPT objectives as enunciated by Meier et al. (2018) and Heidenstrøm (2022). Intervention points may therefore be by eliminating some material elements that can disrupt the interconnecting pushcart vendors' habits that render food vulnerable to contamination. For example, sales with pre-packaged take-away food packs will remove the need for plates, dishing spoons and wash water during sales and eliminate the handling process that exposed food in the environment. The commonly sold foods as shown in Table 2 can all be easily packaged and sealed in disposable plastic containers.

The use of disposable plastic containers to package food is a common practice during celebrations (e.g. birthdays, marriages, funerals) in Nigeria. It can also be extended to pushcart street foods. Intervention in the context of the meaning elements would be to reduce patronage in sales environment where the pushcart food is vulnerable to contamination. The income reduction that will follow can compel the pushcart food vendors to move to other locations without the need for forceful ejection. This can be achieved by promoting building of

restaurants in Parks and market areas or any other crowded environment in order to divert attention from pushcart foods. However, the option of take-away pre-packaged food should be more attractive because the informal economic sector which provides income opportunities for many families need to be sustained.

It can be inferred from the outcome of this study that the potential of using SPT for pushcart food protection and possibly other street foods exists. It has always been difficult to convince people to change behaviour (Conner & Norman, 2017), especially when it involves income generation activities. Compliance with hygienic rules and food protection code of conduct would be seen as an encumbrance to income generation by street food vendors. This is further worsened by the finding that the pushcart food business is dominated by poorly educated women. Mass media enlightenment programmes or seminars on food safety are not likely to induce behavioural changes. The outcome of this study if implemented can limit cases of food-borne diseases associated with street foods and save cost. As we say in Nigeria, "prevention is better than cure",

Non-Governmental Organisations (NGO) that deal with food protection are not common in Nigeria hence the responsibility of ensuring food safety falls squarely on the shoulders of local Government or municipal Public Health Agencies. These agencies can promote patronage of pre-packaged street foods and seek subsidies for packaging materials to make them affordable to street food vendors. The public health agencies should also consider encouraging the emergence of NGOs that can promote food protection in the face of limited resources.

The outcome of this study should be applicable to other urban areas in Nigeria such as Lagos the Nigerian commercial capital located in South West region and Kano the largest commercial centre in Northern Nigeria. Pushcart street foods are numerous in Lagos and Kano where workers leave their homes for work as early as 4 am without breakfast in order to beat traffic jams. The outcome can also apply to stationary street food outlets in stalls, under large canopy trees or large umbrellas because the major difference with pushcarts is mobility. The sales environment and handling habits tend to be identical. However, investigations are still necessary for authentication.

4.1. Study Limitations

Permissions to observe kitchen cooking practices and the transfer of food to warmers or pots were generally denied. Attempts at following the pushcarts vendors to their final sales destinations were viewed with suspicion and rebuffed. Thus, pre-sales information bothering on hygienic practice in the kitchens could not be ascertained. While it is important to identify potential sources of microbial contaminants in the kitchens, the absence of such information does not really affect the reliability of the conclusions. The reason is that the absence of coliform bacteria as indicators of potential contamination in the tested rice meals at the point of commencement of sales suggests that either the cooking process eliminated microbial hazards or their entry was prevented. Thus, the data collected from the sales points was sufficient to test the applicability of SPT for pushcart food safety assurance. However, it is possible to overcome the reluctance of pushcart vendors in granting access if Public Health Agencies are empowered by law to undertake routine inspections of kitchens that serve the public. Access to kitchens by researchers may subsequently be facilitated by the Public Health Agency.

4.2. Future Research Directions

Pre-sales information is necessary in order to completely rule out any iota of doubt concerning the applicability of SPT. In order to fully assess the potential of SPT beyond pushcart foods, future studies concerning hawkers and stationary street food outlets' operators are important. It will also be interesting to extend investigations to other regions in Nigeria for the purpose of ascertaining the influence of cultural and ethnic differences in the Nigerian setting.

5. Conclusion

The SPT-based analysis revealed that pushcart vendors' practices associated with the material elements (plates, dishing spoons, wash-water and food) and handling (competence) compromised food safety. The handling practices exposed the materials to the environment, which was confirmed by the presence of coliform and *Salmonella* bacteria on the materials. The sanitary conditions of the pushcart major sale points (Motor Park, markets, workshops and construction sites) were generally poor and characterised by airborne coliform bacteria. The significant association between the occurrence of coliforms on the materials and the environment showed interconnections between materials, competence and the environment; and indicated that an intervention aimed at disrupting the interconnections can promote food safety as envisioned by SPT. Thus, the vulnerable material elements, handling and sales environment can be considered points for a disruptive intervention. This can be achieved by promoting sales of only pre-packaged food thereby limiting exposure of food and eliminating the usage/need for the vulnerable materials (plates, dishing spoons and wash water).

Acknowledgment

The authors gratefully acknowledge the fieldwork assistance of the 2018 and 2019 final year students of the Department of Microbiology, Delta State University, Abraka Nigeria.

Conflict of Interest

The authors declare no conflict of interest.

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http://foodbulletin.net

FOOD BULLETIN
e-ISSN: 2979-9848

https://prensip.gen.tr

REVIEW ARTICLE

Sustainable Food Ingredients: Micro-Algae as Source Bioactive Compounds

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ARTICLE INFO

Article History
Received: 27.11.2024
Accepted: 26.12.2024
First Published: 30.12.2024

Keywords
Bioactive compounds
Food sustainability
Functional additives
Micro-algae
Sustainable ingredients

ABSTRACT

Microalgae hold immense promise as a sustainable, bioactive source of functional food additives, presenting a unique profile of polyunsaturated fatty acids (PUFAs), carotenoids, vitamins, peptides, and polysaccharides with notable health benefits. Known for their ability to produce compounds like astaxanthin and lutein, *Haematococcus pluvialis*, *Chlorella zofingiensis*, and *Spirulina* contribute to antioxidant, anti-inflammatory, cardiovascular, and visual health when incorporated into food products. Unlike traditional crops, microalgae cultivation requires fewer resources (minimizing land, water, and carbon footprint) while achieving higher photosynthetic efficiency, making them a sustainable solution well-aligned with modern food production goals. However, despite their potential, the mainstream adoption of microalgae-derived bioactives is limited by challenges such as high production costs, complex extraction processes, and stringent regulatory barriers, particularly in markets like the EU. To address these limitations, advancements in photobioreactor technology, biorefinery approaches, and genetic engineering have shown promise in enhancing yield and reducing costs, thereby positioning microalgae as economically viable alternatives to synthetic additives. Furthermore, innovations in encapsulation and bioavailability improvement are advancing, making microalgal compounds more effective and stable in various food systems. This article explores the significant role microalgae could play in food sustainability, reviewing recent research and industry insights to propose practical solutions that encourage broader integration of microalgal bioactives in global markets. Through strategic technological improvements and supportive policy frameworks, the food industry could embrace microalgae-derived compounds, paving the way for resilient food systems that address consumer demands for natural, health-promoting ingredients. With ongoing academic and industrial collaboration, microalgae's high nutritional value and environmental benefits can be leveraged to support both human health and ecological sustainability, signifying their crucial place in future food innovation.

Please cite this paper as follows:

Baldemir, P., & Çaklı, Ş. (2024). Sustainable food ingredients: Micro-algae as source bioactive compounds. *Food Bulletin*, *3*(2), 34-40. https://doi.org/10.61326/foodb.v3i2.315

1. Introduction

Micro-algae are increasingly attracting attention due to their superior nutrient profiles and environmentally sustainable cultivation methods. Microalgae can produce a variety of bioactive compounds and their photosynthetic efficiency is significantly higher than that of land plants, including carotenoids, polyunsaturated fatty acids (PUFAs), proteins and polysaccharides (Ambati et al., 2014). With these characteristics, microalgae stand out as a viable solution to address the global need for sustainable, healthy food additives by both meeting nutritional needs and minimizing environmental concerns.

The cultivation of microalgae is resource efficient as it requires significantly less water and arable land than

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conventional crops. This strengthens their role in sustainable food systems (Bernaerts et al., 2018; Caporgno & Mathys, 2018). Of particular interest is the production of astaxanthin, an antioxidant derived from *Haematococcus pluvialis*, with applications in dietary supplements, cosmetics and functional foods. Reflecting growing consumer demand for natural bioactives, the global astaxanthin market is estimated to exceed $2.57 billion by 2025 (Pan-utai et al., 2021). Likewise, species such as Chlorella are recognized for their rich composition of essential fatty acids, pigments, and albumen, which makes it ideal for enhancing the functional and nutritional properties of foods (Caporgno & Mathys, 2018).

Despite their potential, several challenges hinder the mainstream adoption of microalgae in the food industry. The high cost of production, the technical complexity associated with the extraction of biomass, and the regulatory restrictions, especially in the European Union, are significant barriers (Bernaerts et al., 2018). Advances in biorefinery processes and genetic engineering offer promising solutions by increasing yields and reducing costs, enabling microalgae to become seamlessly integrated into global food systems (Ambati et al., 2014). Furthermore, the urgency to adopt natural and sustainable alternatives is underscored by the shift away from synthetic food additives as consumers prefer clean-label products.

In this review, we focus on primary and secondary metabolites, production challenges, and commercialization strategies to critically assess the bioactive potential of microalgae. A synthesis of recent academic and industrial knowledge is provided to identify ways to scale up the use of microalgae as sustainable food ingredients.

2. High-Value Microalgae Primary Metabolites

2.1. Polyunsaturated Fatty Acids (PUFAs)

Microalgae are a sustainable and efficient source of polyunsaturated fatty acids (PUFAs), including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). These fatty acids are important for cardiovascular health, neural development, and inflammation regulation. In contrast to traditional sources of fish oil, the cultivation of microalgae addresses environmental issues such as overfishing and greenhouse gas emissions, providing an environmentally friendly alternative. Some strains, such as *Crypthecodinium cohnii* and *Phaeodactylum tricornutum*, are especially notable for their high levels of DHA and EPA, accounting for 60% and 30 to 40% of their respective lipid profile (Mendes et al., 2009; Qiao et al., 2016). In a similar way, *Schizochytrium sp*. has been recognized for its ability to accumulate DHA to a level of more than 50% of its lipid composition, which makes it highly suitable for applications in functional foods and nutraceuticals (Torres-Tiji et al., 2020).

Advances in cultivation techniques have also enhanced the production of lipid-rich biomass. For instance, *Auxenochlorella protothecoides* achieves lipid contents of up to 70% of its dry weight under optimized conditions, supporting scalable production of omega-3 fatty acids (Patel, et al., 2018). The health benefits of microalgal PUFAs are extensive, ranging from reducing systemic inflammation to improving lipid profiles and supporting cognitive health (Caporgno & Mathys, 2018). These qualities have driven their incorporation into diverse consumer products, including infant formulas, dietary supplements, and functional beverages.

The unique ability of microalgae to provide a sustainable source of bioavailable omega-3 fatty acids underscores their transformative potential within the global food industry. As demand for plant-based alternatives continues to rise, microalgae-derived PUFAs present a compelling solution that bridges the gap between environmental sustainability and human health.

2.2. Polysaccharides

Polysaccharides derived from microalgae exhibit diverse functional and bioactive properties, rendering them invaluable in both the food and pharmaceutical industries. These structural carbohydrates are renowned for their immunomodulatory, anti-inflammatory, antiviral, and cytotoxic effects, which position them as both therapeutic agents and functional food components (Challouf et al., 2011; Jo et al., 2010). For example, sulphated polysaccharides from *Tetraselmis suecica* are effective in inhibiting inflammatory mediators such as nitric oxide (NO), interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-alpha), demonstrating their potential in the treatment of inflammatory diseases (Jo et al., 2010). Additionally, polysaccharides from *Arthrospira platensis* demonstrate cytotoxicity against colon and kidney cancer cells, underscoring their potential applications in oncology (Challouf et al., 2011).

Certain species, such as *Navicula directa*, produce antiviral polysaccharides effective against influenza and herpes simplex viruses, broadening their utility in combating viral infections (Lee et al., 2006). Beyond therapeutic applications, polysaccharides from *Porphyridium cruentum* and *Chlorella stigmatophora* are notable for their antioxidant and immune-enhancing properties, which make them attractive as natural additives in functional foods (Bernaerts et al., 2018; Mtaki et al., 2020). These bioactive compounds also function as natural thickeners or stabilizers, offering clean-label alternatives to synthetic food additives while enhancing texture and shelf life (Ambati et al., 2014).

Innovative extraction techniques, such as ultrasound-assisted methods, have improved the accessibility and cost-efficiency of microalgal polysaccharides, paving the way for their incorporation into health-focused and environmentally

sustainable products (Bernaerts et al., 2018). Their multifunctional nature ensures their relevance across therapeutic, functional, and clean-label food markets, offering promising avenues for future development.

2.3. Vitamins

Microalgae represent a potent source of essential vitamins, offering significant nutritional and therapeutic benefits that position them as natural biofortifiers in food systems. Species such as *Chlorella vulgaris* and *Nannochloropsis gaditana* are particularly rich in B vitamins, including B2, B3, and the rare B12, which supports energy metabolism and neurological health. *Chlorella vulgaris* provides B12 concentrations ranging from 0.3 to 3.2 mg/kg, addressing a critical dietary gap in plant-based diets (Ljubic et al., 2020; Mehariya et al., 2021).

In another study shows that S. maxima, a species of algae widely cultivated for human consumption, contains up to 71% crude protein with high levels of vitamin B1, vitamin B2, and adequate concentrations of all essential amino acids except those containing β-carotene and sulfur (Clément et al., 1967). Since protein is thought to be the most expensive nutrient in animal feed, developing natural alternatives to soybean meal may be cost competitive (Lum et al., 2013).

In addition to water-soluble vitamins, microalgae such as *Dunaliella bardawil* serve as excellent sources of pro-vitamin A and vitamin E, promoting immune function, skin health, and antioxidant defense (Pan-utai et al., 2021). Furthermore, *Tetraselmis chuii* and *Euglena gracilis* produce abundant vitamin C, enhancing their appeal as natural fortification agents. Notably, *Arthrospira maxima* and *Tetraselmis suecica* also contain significant amounts of vitamin D, critical for bone health and immune regulation, with concentrations reaching up to 14 mg/g (Ljubic et al., 2020).

The ability of microalgae to produce a wide range of bioavailable vitamins, including antioxidants like vitamins C and E, aligns with consumer demand for natural, health-promoting food ingredients (Torres-Tiji et al., 2020). This exceptional nutrient density makes microalgae an attractive alternative to synthetic vitamin fortification, offering sustainable solutions to combat dietary deficiencies while supporting the clean-label trend.

2.4. Peptides

Peptides derived from microalgae have emerged as valuable bioactive components with multifunctional health benefits. Species such as Spirulina and *Chlorella vulgaris* are particularly rich in protein, with up to 70% of biomass composed of peptides known for their antioxidant, antimicrobial, and antihypertensive properties (Ambati et al., 2014; Bernaerts et al., 2018). These bioactive peptides contribute to food preservation and human health by reducing oxidative stress, inhibiting microbial growth, and promoting cardiovascular health.

For instance, hydrolyzed peptides from *Chlorella vulgaris* exhibit potent free radical-scavenging activity, neutralizing harmful hydroxyl and superoxide radicals (Mtaki et al., 2020). Similarly, enzymatic hydrolysates from *Navicula incerta* demonstrate significant antioxidant effects, offering potential therapeutic applications in managing oxidative stress and metabolic disorders (Heo et al., 2005). These peptides also enhance food functionality and texture, aligning with the growing demand for natural and multifunctional food additives.

Advanced enzymatic hydrolysis techniques have further optimized the extraction of bioactive peptides, enhancing their therapeutic efficacy and commercial viability. As natural alternatives to synthetic additives, microalgal peptides hold significant potential for innovation in both functional food and nutraceutical markets.

3. High-Value Microalgae Secondary Metabolites

3.1. Phytosterols

Phytosterols extracted from microalgae species like Nannochloropsis and Chlorella have shown significant cholesterol-lowering properties. Structurally similar to cholesterol, these compounds compete with dietary cholesterol for intestinal absorption, reducing LDL cholesterol levels and lowering the risk of cardiovascular disease (Nollet & Ahamad, 2024). This mechanism provides a sustainable alternative to pharmacological lipid-lowering agents, particularly for individuals with hypercholesterolemia (Moghadasian & Frohlich, 1999).

The integration of microalgal phytosterols into functional foods addresses consumer demand for heart-healthy, natural ingredients. Their dual role as therapeutic agents and sustainable alternatives to synthetic cholesterol-lowering compounds underscores their transformative potential in the nutraceutical and functional food industries.

3.2. Mycosporine-Like Amino Acids (MAAs

Mycosporine-like amino acids (MAAs) are unique compounds synthesized by certain microalgae, notably red algae such as Porphyridium. These bioactive molecules serve as natural photoprotective agents, absorbing ultraviolet (UV) radiation and mitigating oxidative damage to cellular components such as DNA and proteins (Garcia-Pichel & Castenholz, 1993). This functionality renders MAAs particularly valuable in applications related to skincare and sun protection.

Beyond their role in UV defense, MAAs exhibit potent antioxidant properties that delay oxidative spoilage in food products, thereby extending shelf life while simultaneously

delivering health benefits (Ambati et al., 2014). Their multifunctionality (including UV absorption, antioxidant activity, and photoprotection) makes them appealing for incorporation into anti-aging and photoprotective formulations in the cosmetic and food industries (Pan-utai et al., 2021). By offering natural, sustainable solutions to combat oxidative stress and radiation damage, MAAs align with increasing consumer preferences for eco-friendly, health-enhancing products.

3.3. Pigments

3.3.1. Phenolic compounds

Phenolic compounds produced by microalgae, including flavonoids and phenolic acids, are renowned for their antioxidant, anti-inflammatory, and anticancer properties. Species such as Phaeodactylum tricornutum, *Chlorella vulgaris*, and *Haematococcus pluvialis* produce bioactive phenolics, including apigenin, genistein, and p-coumaric acid, which exhibit strong therapeutic potential (Goiris et al., 2012). For example, apigenin promotes autophagy in leukemia cells, while ferulic acid and p-coumaric acid demonstrate robust free radical scavenging activities, reducing oxidative stress and enhancing cellular health (Heo et al., 2005).

Beyond health benefits, phenolic compounds act as natural preservatives, delaying lipid peroxidation and enhancing food stability. This dual functionality underscores their importance in developing functional foods and nutraceuticals that prioritize both sustainability and health outcomes (Goiris et al., 2012).

3.3.2. Chlorophyll

Although food processing effects are well established, a more complete understanding of chlorophyll derivatization by digestion, the extent to which chlorophyll derivatives are absorbable, and the absorption and formation of any specific chlorophyll metabolites is absolutely necessary to better understand the role these pigments may play in the prevention of chronic diseases (Ferruzzi & Blakeslee, 2007).

Chlorophyll, abundantly found in Chlorella and Spirulina, serves as a natural green colorant and detoxifying agent. Its health benefits, including support for liver function and improved digestion, enhance its appeal in health-oriented and detox products (Ambati et al., 2014; Caporgno & Mathys, 2018).

The growing interest in the potential chemopreventive effects of chlorophyll stems from its role as a class of plant pigments associated with cancer prevention, particularly in diets rich in phytochemicals. Chlorophyll derivatives, traditionally used in medicine, are notable for their low toxicity, making them promising candidates as anti-cancer and therapeutic agents. The following sections explore studies that detail the in vitro and in vivo bioactivity of chlorophyll, along with the potential mechanisms underlying its anti-cancer actions (Harrison et al., 1954; Kephart, 1955).

In another study, consuming chlorophyll at each meal led to an overall 55% reduction in mean urine levels of the aflatoxin biomarker compared to those taking a placebo. Therefore, prophylactic interventions or supplementing the diet with chlorophyll-rich foods may be a practical way to prevent the development of hepatocellular carcinoma or other cancers of environmental origin (Egner et al., 2001).

3.3.3. Phycobiliproteins

Phycobiliproteins, such as phycocyanin and allophycocyanin, are vibrant protein-based pigments synthesized by microalgae, including *Spirulina platensis*. These pigments serve dual roles as natural colorants and bioactive compounds, exhibiting antioxidant, anti-inflammatory, and hepatoprotective properties (Citi et al., 2024). Phycocyanin, for example, has demonstrated potential in managing oxidative stress, inflammatory diseases, and liver conditions, making it suitable for functional foods and nutraceuticals (Eriksen, 2016).

Moreover, allophycocyanin offers immunomodulatory and anti-inflammatory benefits, further enhancing its value in addressing chronic health conditions. These pigments' ability to combine aesthetic appeal with therapeutic functionality positions them as innovative alternatives to synthetic dyes, catering to health-conscious and sustainability-focused markets (Lucas et al., 2018).

3.3.4. Carotenoids

Carotenoids, including astaxanthin, lutein, β-carotene, and fucoxanthin, are among the most valuable microalgal metabolites due to their potent antioxidant properties and diverse health benefits. Astaxanthin, derived primarily from *Haematococcus pluvialis*, is particularly notable for its superior antioxidant capacity, neuroprotective effects, and applications in cardiovascular health and skincare (Ambati et al., 2014; Jannel et al., 2020; Shah, et al., 2016).

Astaxanthin has demonstrated significant anti-inflammatory properties in an in vitro study using LPS-stimulated RAW264.7 mouse macrophage cells. It was shown to inhibit the synthesis of proinflammatory mediators, including nitric oxide (NO) and prostaglandin E2 (PGE2), which are produced by inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2), respectively. Additionally, astaxanthin suppressed the production of key cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-1 beta (IL-1β). A notable mechanism underlying these effects is its ability to inhibit the activation of nuclear factor kappa B (NF-κB), a transcription factor that regulates the expression of proinflammatory genes, including iNOS, COX-2, TNF-α, IL-1β, and interleukin-6 (IL-6). Astaxanthin also reduced iNOS

promoter activity and directly inhibited intracellular reactive oxygen species (ROS) accumulation, as well as hydrogen peroxide (H2O2)-induced NF-κB activation and the subsequent expression of iNOS and COX-2. Furthermore, it blocked nuclear translocation of the NF-κB p65 subunit and prevented the degradation of IκB-α by inhibiting IκB kinase (IKK) activity. These findings collectively indicate that astaxanthin suppresses inflammatory mediator production through a multifaceted mechanism involving the inhibition of NF-κB activation, IKK activity, and IκB-α degradation (Lee et al., 2003).

Lutein, abundant in Chlorella and *Dunaliella salina*, supports eye health by mitigating risks of macular degeneration and cataracts (Nwachukwu et al., 2016). Meanwhile, β-carotene serves as both a natural food colorant and a precursor to vitamin A, with immune-boosting and skin-protecting properties that cater to clean-label preferences (Bernaerts et al., 2018). Fucoxanthin, found in *Chaetoceros sp*., exhibits anti-obesity, anti-diabetic, and anticancer properties, making it a promising candidate for metabolic health interventions (Fernandes & Mamatha, 2023).

Although production costs remain high for certain carotenoids like astaxanthin, advancements in photobioreactor genetic engineering and technologies continue to enhance yield and cost-efficiency, solidifying their role in sustainable food systems (Pan-utai et al., 2021).

4. Conclusion

Investigating bioactive compounds derived from microalgae highlights their significant potential as sustainable and multifunctional food additives. Microalgae provide a variety of compounds, including polyunsaturated fatty acids (PUFAs), vitamins, peptides, and secondary metabolites like carotenoids, chlorophyll, and phytosterols, meeting contemporary consumer preferences for natural, health-enhancing, and eco-friendly ingredients (Ambati et al., 2014; Caporgno & Mathys, 2018; Pan-utai et al., 2021). Positioning microalgae as a key contributor to functional food innovation, these compounds offer health benefits ranging from antioxidant and anti-inflammatory effects to cardiovascular and vision support (Cioanca et al., 2024)

Moreover, the ecological benefits of microalgae cultivation—including reduced water and land use and compatibility with controlled growth systems—highlight their suitability as a sustainable food source. Microalgae such as Schizochytrium and Nannochloropsis exemplify the ability to produce eco-friendly omega-3 fatty acids, addressing the growing demand for plant-based alternatives while alleviating pressure on marine ecosystems (Pan-utai et al., 2021).

Despite these advantages, challenges such as high production costs, complex extraction processes, and regulatory hurdles must be addressed to enable widespread commercialization. Innovations in cultivation methods, including photobioreactors and genetic engineering, show promise in reducing costs and enhancing yields, but further research and policy support are essential (Bernaerts et al., 2018; Pan-utai et al., 2021).

In summary, microalgae offer a compelling solution to the dual imperatives of health promotion and environmental sustainability in food systems. As advancements in technology and regulation progress, microalgal bioactives hold the potential to revolutionize global food markets, paving the way for a more sustainable and health-focused future (Ambati et al., 2014; Caporgno & Mathys, 2018).

Conflict of Interest

The authors declare no conflict of interest.

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http://foodbulletin.net

FOOD BULLETIN
e-ISSN: 2979-9848

https://prensip.gen.tr

REVIEW ARTICLE

Developments in Radiofrequency Processing Applications on Food of Animal Origin

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ARTICLE INFO

Article History
Received: 10.12.2024
Accepted: 27.12.2024
First Published: 30.12.2024

Keywords
Dielectric heating
Meat
Novel technique
Radiofrequency
Seafood

ABSTRACT

Radio frequency (RF) treatment is one of the novel dielectric heating techniques for foods. It is an indirect process whereby electrical energy is initially transformed into electromagnetic radiation, which then generates heat within the food. Radiofrequency heating has been found some advantages like rapid heating or deep penetration into food compare to conventional methods. Traditional heat treatments applied to animal products can lead to quality losses, color and texture changes, overheating problems and other undesirable side effects. RF treatment has the potential to minimize these problems, improve organoleptic quality, reduce process time and save energy. Recently, the most investigated methods for animal origin foods are RF pasteurization/sterilization, RF-supported thawing methods, RF heating or cooking and the results obtained are promising. Radiofrequency technique is also investigated for following purposes; blanching, post-bake drying, roasting and disinfection. The new generation of RF studies explore other aspects, including the discovery of dielectric properties of foods, the evaluation of efficiency and quality effects, environmental sustainability of RF technologies and the improvement of RF system performance. Also combined systems are investigated such as radiofrequency-assisted cryogenic freezing. This paper reviewed principles of RF, overview situation of RF treatment methods and recent literature on RF applications on food of animal origin.

Please cite this paper as follows:

Yildiz Turp, G., & Ozuesen, S. (2024). Developments in radiofrequency processing applications on food of animal origin. *Food Bulletin*, *3*(2), 41-51. https://doi.org/10.61326/foodb.v3i2.320

1. Introduction

In recent years consumers demand that foods sold in markets have similar sensory properties to fresh foods and maintain their quality with minimal processing. Many new technologies have been and continue to be studied by researchers and industry to make the final products suitable for this demand. These technologies include both thermal and non-thermal processes. Microwave, high hydrostatic pressure, ultrasound, ohmic treatment and radiofrequency (RF) are some of the novel techniques applied in food technology.

RF is grouped together with microwave as non-ionizing radiation. RF is also called high frequency dielectric heating (Laycock et al., 2003). RF waves in the range of 1 to 300 MHz (Yao et al., 2022).

Radio frequency can heat food faster and more efficiently because it utilizes different parts of the electromagnetic energy spectrum. In contrast to conventional heating systems where heat energy is transferred from a hot medium to a cooler product resulting in large temperature gradients, electro-heating

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involves the transfer of electromagnetic energy directly into the product. This initiates volumetric heating due to frictional interaction between water molecules and charged ions. In this system heat is generated within the product. The efficacy of these modes of heating is generally higher than that of traditional conduction or convection heating modes (Koutchma, 2022). In traditional RF heating, such as in parallel plate electrode systems, the electromagnetic field is usually generated in a directional way between the electrode plates while the electromagnetic field of microwave heating might approach the material from different directions (Huang et al., 2018; Llave & Erdogdu, 2022).

The potential of RF technology has been known since 1940s. Initial research attempts efforts laid the groundwork for the industrial application of RF technology by identifying its potential and associated constraints. RF heating has been shown to obtain effective pasteurization or sterilization. Microbial or pest inactivation by RF heating is based on reversible/irreversible deformation of cell members (Ştefănoiu et al., 2016). There are many studies investigating the use of the RF technique on meat products for pasteurization or sterilization (Ballom et al., 2021; Wang et al., 2022a; Wei et al., 2019) and pasteurization and disinfection (Bermudez-Aguirre & Niemira, 2023). Wang et al. (2022a) evaluated pilot-scale pasteurization system for beef sausages. Sausages were pasteurized only RF energy (27.12 Mhz, kW). They mentioned that result of the study showed RF system has a great potential to pasteurize solid foods like beef sausages.

Studies also showed that RF systems can preserve physicochemical components of foods better. As reported by Fiore et al. (2013), RF oven treatment preserved ascorbic acid and increased glucosinolates concentration in broccoli and it decreased the formation of acrylamide in roasted potatoes more than 50%. Similarly, the total amount of vitamin B in salmon was 30% and 50% higher in RF cooking system than those of conventionally cooking method. In addition to the use of RF for these purposes, it has also been investigated for drying (Chen et al., 2022; Huang et al., 2022), tempering (Han et al., 2022; J. Jiang et al, 2021), cooking or baking (Hussain et al., 2021; Q. Jiao et al., 2022; Saka et al., 2021). While studies on meat have predominantly centered on pasteurization/sterilization and thawing, the impact of the RF on product quality has been less explored. Wang et al. (2022b) was used to RF (27.12 MHz, 6 kW) combined superheated water (SW) system to inactivate *G. stearothermophilus* spores in ready-to-eat poached spicy pork slices. Result showed combined RF with SW under 170 mm electrode gap provides reduction in *G. stearothermophilus* spores and kept good sensory evaluation. Jantapirak et al. (2021) investigated effect of RF technology on the quality properties of vacuum-packed nitrite-free sausages and concluded that shorter process time of RF system promoted good texture and cooking yield safely for this products.

According to the US Food and Drug Administration (FDA), RF waves can be used to heat food safely if the radiation source must consist of electronic equipment that produces radio frequencies at specific frequencies determined by the FCC (Federal Communications Commission) and the radiation used or intended to be used in the production of food must have an effect on the process (Cakmak & Tavman, 2011).

An additional application area of the RF field is the utilization of radio frequency identification (RFID) technology. RFID technology is a non-contact automatic identification technology that enables the automatic identification and data acquisition of target objects through the use of radio frequency signals (Yiying et al., 2019). RFID is an alternative technology with a potential to replace traditional universal product code (UPC) barcodes. This system is applicable to the food industry and meat products.

Current studies about RF technology mostly focus investigate pasteurization or sterilization potential, thawing freeze foods, tempering and discuss distribution during RF treatment. The new generation of RF studies explore other aspects, including the discovery of dielectric properties of foods, the evaluation of efficiency and quality effects, environmental sustainability of RF technologies and the improvement of system performance.

Thus, this review's purpose is to introduce RF technology, give basic information's about RF heating principle and summarize its novel application in food of animal origin.

2. History of RF

In 1873 James Clerk Maxwell mathematically predicted the existence and behavior of radio waves and after him Heinrich Henz experimentally proved Maxwell's theory in 1885. RF technique has been used for various food processes for over 80 years since the 1940s. At the beginning it was used or studied for blanching vegetables or thawing frozen foods. In the 1960s most of the studies focused on using RF energy for thawing or defrosting frozen foods. Some of the studies were successful and they applied to production lines. After a while RF has also been adapted for pasteurization of meat products (Marra et al., 2009). The next step in RF was post-bake drying of cookies and snacks in the 1970s. In the 1990s, the use of the RF technique for pasteurization became widespread, and studies on this subject were conducted with greater frequency. Subsequently, research into resolving technical issues associated with this technique intensified (Huang et al., 2018). Figure 1 shows the number of publications about radiofrequency on food of animal origin since 2017 according to Scopus Database.

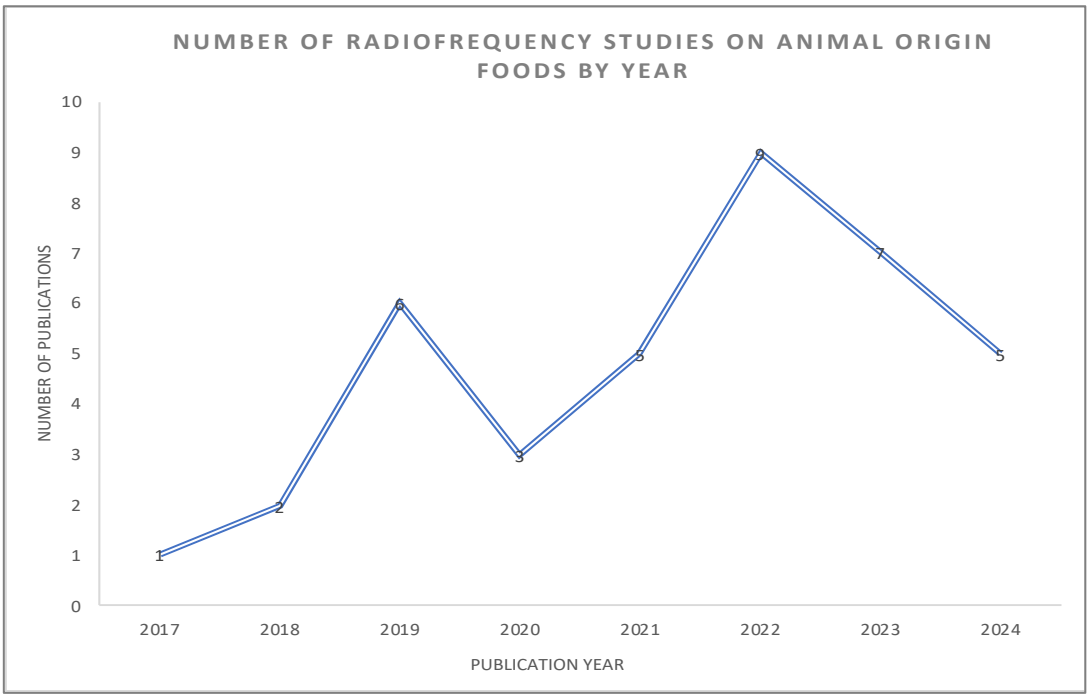

Figure 1. Number of publications about radiofrequency on food of animal origin since 2017 ((Information obtained from Scopus Database on 17 November 2024).

3. Principle and Mechanism of RF

RF is electromagnetic waves in the range of 1 to 300 MHz (Yao et al., 2022). Only certain values are used scientifically and industrially in order not to affect other systems such as communication and military.

Figure 2 and 3 shows the electromagnetic spectrum and comparison of wavelengths with different objects respectively.

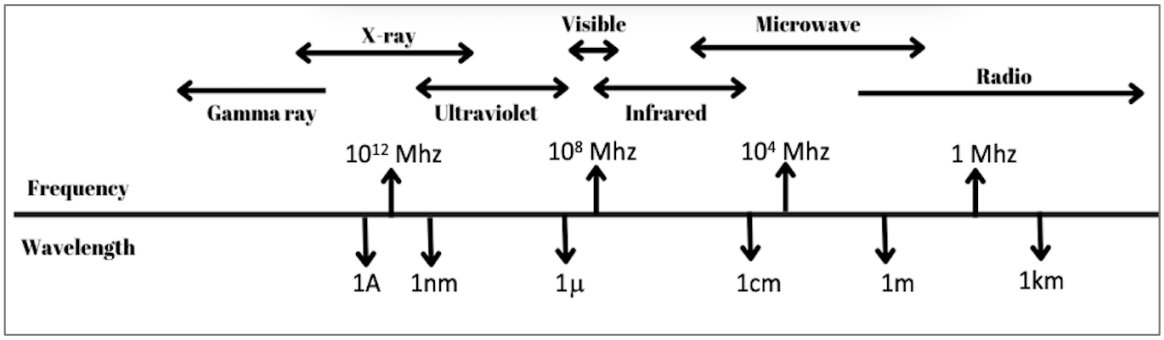

Figure 2. Electromagnetic spectrum (Yazar & İçier, 2013).

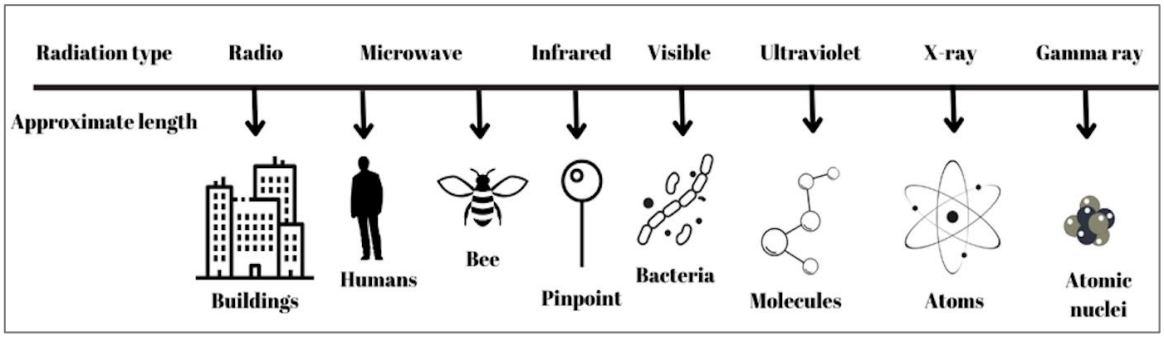

Figure 3. Comparison of wavelengths with different objects adapted by (STScI.''NasaHubblesite'').

The principle of the RF system is based on high-frequency radio waves generated by two electrodes fed with high-voltage alternating current. In systems that generate radio waves, the electrical energy is converted into electromagnetic energy. This energy is absorbed by the food as internal energy and this internal energy creates heating procedure. At low frequencies, within the radio frequencies, ionic depolarization is considered to be the dominant mechanism of heating (Marra et al., 2009). Dielectric heating includes two primary mechanisms which are ionic depolarization and dipole rotation. Ionic depolarization means ions in the food material exposed to the swiftly oscillating in electrical field of RF waves and this situation caused heat occurrence. Dipole rotation means dipolar molecules like water molecules rotate incessantly to acclimatize with the changing electrical field. In RF heating, electrical field acts like a big magnet which that's incessant flipping its poles. So, the tinnier magnets try to catch up to stay in the right direction. This never-ending state of keeping up first creates friction and subsequently heat. (Altemimi et al., 2019; Di Rosa et al., 2019; L. Liu et al., 2024). Ionic depolarization is a more significant factor in RF heating than dipole rotation (Y. Jiao et al., 2018). General system specifications of RF system for use in foods are given in Table 1

Table 1. General system specifications of RF for use in foods (Y. Jiao et al., 2018).

Design characteristics of RF system use in foods	
System	Simple
Heating technique	Ionic depolarization has
Frequencies (MHz)	13.56 / 27.12 / 40.68
Wavelengths (in vacuum / m)	22.1, 11.1, 7.4
Penetration depth (in tap water /m)	1.58 / 0.79/ 0.53

RF waves applied in lower frequencies. Lower frequencies would always associate with larger wavelength according to:

$$c=\lambda\nu$$

Where c is the speed of light, λ is wavelength (m) and ν is frequency of the wave (Hz). Lower frequencies are better to control of the absorbed power by material or product. Hence, RF creates more controllable and balanced temperature increase. Higher wavelength means larger penetration depth. Thus, RF can reach more larger area. The low frequency and large wavelength of RF systems make enable volumetric heating (Awuah et al., 2015; L. Zhang et al., 2021) This is the key of RF technique. RF technique heat volumetrically, while traditional techniques provide surface heating (L. Zhang et al., 2021). Figure 4 shows the schematic drawing of a radio-frequency heating (RF-H) system.

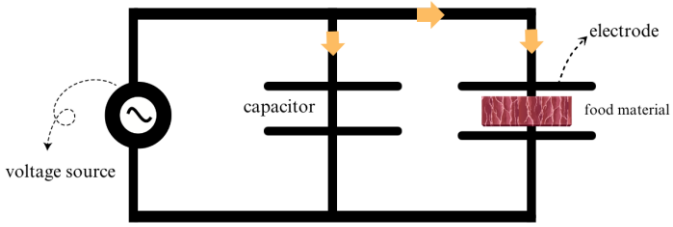

Figure 4. Schematic drawing of a radio-frequency heating (RF-H) system adapted by Altemimi et al. (2019).

RF heating has great potential to reduce the number of microorganisms. Electroporation generates pores in the cell membrane, and the electromagnetic impact may lead to the destruction of DNA and proteins (Guo et al., 2019; H. Zhang et al., 2020). Table 2 presents an overview of the advantages and disadvantages observed in the radiofrequency system.

Table 2. Advantages and disadvantages of radiofrequency system (Marra et al., 2009; Obileke et al., 2022; Ravishankar, 2019).

Advantages of RF	**Disadvantages of RF**
High thermal efficiency	RF works well with large units, but not as well with small units as large units.
RF heating does not have any requirement for direct contact between product and electrode	The operating and equipment costs
More uniform heating over sample geometry	Users may need to know some high-level knowledge
RF can penetrate much deeper into samples without surface overheating	Slow heating rate
Hot/cold spot development observes less than MW	Information on dielectric properties of the target product may not be available
Can be applied inside packaging, it allows in-package pasteurization/sterilization	

There are studies which define RF technology as an alternative pasteurization or sterilization process. Several studies shown positive results of RF inactivation including *Enterococcus faecium* and *Salmonella* in wheat flour (S. Liu et al., 2018), *Salmonella* spp. in ground black paper (Wei et al., 2019) and *Salmonella typhimurium* in red paper powder (Hu et al., 2018). Hu et al. (2018) detected that in red pepper powders with a_w of 0.57, *S. typhimuriumin* were reduced 3.2, 3.9 and 5.6 log CFU/g after 180s RF treatment heated to 70°C, 80°C and 90°C, respectively. Initial a_w of food has effect on RF heating profile and pasteurization efficiency (Xu et al., 2019).

4. Application of RF on Food of Animal Origin

Meat and meat products play a crucial role in the human diet. Meat is a primer source of essential amino acids and supplies amino acid derived metabolites and peptides that have important bioactive properties. Iron bioavailability is highest when it is meat origin. Besides that, zinc is hard to consume in diets which include less animal-based foods (Geiker et al., 2021). Furthermore, there is no doubt that processed meat products, such as sausages, meatballs, meat cakes, and various other local delicacies, consistently enjoy high market demand. These products are favored by consumers due to their superior palatability, high nutrient content, and desirable aroma and taste (L. Liu et al., 2024). The most prevalent foodborne pathogens related to meat consumption are *Escherichia coli, Salmonella enterica*, and *Listeria monocytogenes* (Di Rosa et al., 2019). There is a mandatory requirement to take precautions against microbial risks. The RF system is used for melting frozen meats, processing meat products and preserving meat products (Altemimi et al., 2019). There are many studies related to the usage of the RF technique on meat and meat products for pasteurization or sterilization (Ballom et al., 2021; Wang et al., 2022b; Wei et al., 2019).

RF heating system is considered as a method to obtain uniformly heated foods. Besides that, in literature one of the significant issues of RF system mentioned as a lack of temperature uniformity. The main effective factors for uniform heat distribution are classified into three distinct categories food characteristics, RF system features, and application parameters. The primer factor is deflection of electrical field. Determine dielectric and thermal properties of meat products can be challenging due to their complex structure. Different components act differently under electrical field, so their capacity of absorbing electromagnetic energy will be different. Different components of meat could concentrate electrical field in a certain region. As result of this, certain regions heat quicker, the uniformity cannot provide, and hot-cold spots are existing (Goñi et al., 2022). Moreover, Even RF system can work in both batch and continuous, most of studies focus batch process. The meat processing industry relies on large units that must be processed in a shorter time. The absence of continuous process studies in the existing research may hinder the adaptation of this system to the meat industry (Bedane et al., 2017).

Another application area of the RF is the Radio frequency identification (RFID) technology and this system is applicable to the meat industry. RFID technology has the potential to replace traditional universal product code barcodes, enabling automatic identification of target objects and data collection through the use of radio frequency signals (Yiying et al., 2019). Three different type of RFID the near field communication (NFC), chipped RFID, and chipless RFID technologies are proposed. NFC systems are more suitable with shorter distance (1-2 cm) (Fathi et al., 2020). The use of chip-based RFID technologies ensures high accuracy in the reading process; however, this may result in an increase in the complexity and cost of the tag, as well as a reduction in the tag's robustness and ease of integration with the package (Karmakar et al., 2016). Chipless RFID tags demonstrate enhanced functionality in hard and extreme environments. They can be printed on their support structure, similar to barcode tags, using conductive inks. Despite their current high cost, there is more potential for using and development (Vena et al., 2016). The implementation of an RFID system has the potential to represent a significant advancement the field of food traceability. Yiying et al. (2019) proposed a food traceability process and information model based on RFID system to animal origin foods. According to this system, consumers can get information about every step from the birth of the animal to the supermarket.

The majority of studies on meat and meat products concentrate on RF-based thawing/tempering and pasteurization/sterilization processes.

4.1. RF Thawing/Tempering

The traditional method of thawing in the refrigerator (4°C) is ineffective and problematic. It causes slow thawing, a large amount of drip loss and leads to bacterial growth (Y. Jiao et al., 2018). The inappropriate selection of a thawing method will result in a loss of quality, a change in colour, texture, flavor and provides an environment for microbial growth (Llave & Erdogdu, 2022). RF thawing represents a promising method for the thawing of meat and fish products, although it is currently employed only to a limited extent in industry. RF thawing is similar to microwave (MW) thawing. During the process, the product passes through the heater, whereby the heating occurs with radiofrequency energy (Ravishankar, 2019).

Bedane et al. (2018) revealed that RF thawing was 23 times faster than traditional thawing for chicken breast meat. Sun et al. (2023) detected that RF thawing method significantly reduced the thawing time for mutton in comparison to air thawing. RF thawing also preserved better texture, colour and thermal stability in samples. The findings of the study corroborate the concept that RF thawing is an effective approach for reducing thawing time while maintaining product quality. H. Jiang et al. (2023) investigated the potential implications of RF thawing on irregular sea products and the effect of layout position on thawing. The researchers used a 27.12 MHz, 6 kW free-running oscillator radio frequency (RF) heating system with parallel-plate electrodes. The findings of the study indicated that the upright position hairtail fish unevenly heated. In contrast, the flat position hairtail fish exhibited superior thawing performance. This result showed that geometrical structure and position of food material have important effect during RF thawing process.

It has been suggested that a thickness of 5 cm is the optimal dimension for fish block (Ravishankar, 2019). Li et al. (2016) used COMSOL Multiphysisc® software to simulate the RF thawing process to 3 different thickness of beef (1.8cm, 3.8cm, 5.8cm); three different surface areas with constant thickness of 3.8 cm (original, 2 times, 4 times); three different shapes of beef (rectangle, trapezoid, step shape). The result of study showed best results given by 1.8cm, original surface area and step shape beefs. When other conditions remain constant, beef with a small dimension and a high surface area thaws at a faster rate.

As is the case with the majority of thermal thawing processes, the RF method is susceptible to the issue of runaway heat. Furthermore, the RF thawing system necessitates the implementation of rigorous sealing procedures. The system is susceptible to interference from nearby radio transmitters, necessitating the implementation of strong protection measures to ensure its functionality (Cai et al., 2019; Gao et al., 2023).

4.2. RF Pasteurization/Sterilization

RF is powerful method based on electromagnetic waves, has been investigated as a potential pasteurization method to inactivate food microorganisms, such as *Salmonella*, *Bacillus subtilis* spores, and *E. coli* O157:H7 (Uemura et al., 2010; Y. Zhang et al., 2020). Cui et al. (2022) investigated the cellular-level mechanism of action of RF pasteurization. The results of the study indicate that the cellular changes that occur during RF pasteurization include damage to the cell membrane, intracellular leakage of substances, changes in cell morphology, changes in intracellular structure, protein denaturation and changes in gene expression (on a smaller scale). These changes lead to damage to cells and the achievement of pasteurization.

RF system penetrates the inside of food package which allows in-package pasteurization/sterilization. RF pasteurization is particularly beneficial for ready-to-eat meat products as it can be applied after final packaging, reducing the risk of post-processing contamination (Aymerich et al., 2008). Wang et al. (2022b) used a novel device that simultaneously uses radio frequency (RF) energy (27.12 MHz, 6 kW) and superheated water (SW) with different electrode gaps and different water temperatures to inactivate G. stearothermophilus spores in ready-to-eat spicy pork slices. They found that RFSW combine system with 190mm electrode gap results fastest heating rate but resulted in worst quality compared to the conventional method. RFSW combine system with170mm electrode gap sterilization overall reduced the water loss and thermal damage to product. The results of the study demonstrated that a system combining radiofrequency and superheated water has substantial potential for use in the sterilization of ready-to-eat and in-package meat products.

RF enhances the target temperature faster than conventional methods. Heating time is much less than conventional so quality of meat product improves (Y. Jiao et al., 2018). On the other hand, RF pasteurization has not been commercialized yet due to limitations. While RF pasteurization shows promise at the laboratory and pilot scales, further research is needed to optimize protocols for industrial-scale applications (Calero et al., 2022) Combination with other antimicrobial treatments or technologies not investigated enough to apply industrial area (Nagaraj et al., 2016). Table 3 shows the summary of studies about RF technology used on animal origin products since 2017.

RF can positively affect the firmness of meat products by better preserving the water holding capacity of meat. It was stated that the changes in the hardness of meat during process is related to its water holding capacity (Y. Zhang et al., 2022). High-intensity radiofrequency (RF) treatments, particularly pasteurization, can vaporize the bound water inside the meat, allowing it to escape and thereby breaking the protein gel's three-dimensional network structure (Zhao et al., 2020). This results in a reduction in the hardness and chewiness of the meat products. RF thawing/tempering applications can be effective in reducing meat drip loss (Y. Zhang et al., 2022). Bedane et al. (2018) confirmed that RF thawing (10 kW, 27.12 MHz, electrode gaps of 65, 75, and 85 mm) had no significant effect on the texture (hardness, springiness, gumminess, and chewiness) of the thawed chicken breast meat, but markedly reduced drip loss as compared with thawing in a conventional method (refrigerator 4 ◦C).

Table 3. Summary of studies about RF technology used on animal origin products since 2017.

Product / Sample	Parameters / frequency	Aim of study	Conclusion	Reference
Pacific saury (*Cololabi ssaira*)	9kW – 27MHz	To investigate the effects of RF heating and conventional heating method on the elasticity, protein and collagen content of fish bones	The results support that RF heating is a suitable method for obtaining edible bony fish in a short time. The degree of softness achieved in 40 minutes using conventional techniques was attained in 18 minutes through the application of (RF) heating.	Kanafusa et al. (2018)
Marinated chicken breast	27.12 MHz	To develop the process for preheating marinated chicken breast meat in a pilot-scale radio-frequency oven and investigate its effect on marinade pickup, purge, cook yield and shear value.	RF preheating of chicken meat showed a great potential for preheating treatment.	Singh and Deshpand (2019)
Minced Fish	27.12 MHz	Using RF to find a thawing method which causes the least amount of damage possible with shortest time	RF system is considered a reasonable method for thawing minced fish. RF thawing at 27.12 MHz showed considerably greater penetration depth values from −15 °C to −4 °C.	Yang et al. (2019)
Pork Ham	27.120 ± 0.163 MHz	Developing a two-step (RF-tunnel and RF-steam oven) cooking system for pork ham. Also comparing new developed system with only steam-oven.	RF-Steam oven system gived similar results to conventional steam cooking. The RF-Steam oven system reduced necessary time %50.	Muñoz et al. (2020)
Nitrite-free sausages	27 MHz	To determine the effect of RF technology on the quality properties of vacuum-packed nitrite-free sausages. Conventional Retort heating method and RF method were compared.	The RF process was found safe for nitrite-free meat products. There are no significant differences between the inactivation of *B. Subtilis*. However, the shorter time of RF system promoted good texture and cooking yield comparing retort heating.	Jantapirak et al. (2021)
Tilapia (*Oreochromis mossambicus*)	27.12 Hz 600-800-1000 W Electrode gaps 10-12-14 cm	Determine the batch and continuous RF tempering processing parameters and compare the effects of RF technique to those of water tempering.	RF system provided uniform temperature distribution on the surface better than water-bath tempering. RF tempering parameters (800 W , 12cm) was more uniform than other parameters. Also, TBARS results and drip loss of RF treated samples were lower than water-bath treatment. No significant difference found in texture profiles.	Y. Zhang et al. (2021)
Salmon *(Salmo Salar)*	RF tempering: 40.68 MHz WT: + 10 ˚C, 10 ± 0.5 ˚C AT: + 10 ˚C, 10 ± 1 ˚C	Compare effects of different tempering methods: radio frequency tempering, water tempering on the physiochemical properties of salmon fillets	The best overall quality of salmon found in Air Tempering application. However, it has long tempering time, RF is still promising as a new salmon tempering technology	Han et al. (2022)
Chicken meat	46.78 MHz two operative powers (225W and 300W)	Reveal the effect of load spatial configuration on heating rate, temperature uniformity and energy efficiency during RF heating of chicken meat at 40.68 MHz	During RF heating of chicken meat geometrical factors (shape of meat or gap between electrode and sample) were important on the major attributes.	Goñi et al. (2022)
Pork loin	27.12 MHz	Improve meat freezing by combining low-voltage radio frequency (RF) with cryogenic freezing.	In laboratory scale low voltage radiofrequency assisted technology for cryogenic freezing have a potential to obtain frozen meat with increased quality.	Manzocco et al. (2022)
Minced chicken breast	6Kw-27.12Mhz	Combine RF and traditional water bath (WB) for improved gel properties of minced chicken breast	Gel properties of chicken beast improved. Combined system required less time than traditional WB system.	L. Liu et al. (2024)

In general, radiofrequency thawing/tempering can help achieve a color that closely approximates that of the original meat product due to its fast and homogeneous heating process (Han et al., 2022). The difference in color attributes under different RF conditions and applications had a relatively strong correlation with pH, migration of bound water to immobilized water, content of immobilized water, and drip loss during process (J. Jiang et al., 2021). Color differences (ΔE) were lower in sausage samples heated with RF and SW (105°C, 110°C, 115°C and 120°C) compared to samples heated with SW alone (105°C). This was explained by the fact that RF energy shortens the heating time and provides a more uniform heat distribution (Wang et al., 2024). Results of study by Han et al. (2022) showed that the L* value of radiofrequency tempered (RT) salmon fillets was significantly increased compared to those of control samples. While the a* value of samples showed no significant difference compared to control samples, b* value was lower than control samples. Wang et al. (2024) observed that with an increase in temperature during RF process, the L* values of the sample increased while a* values decreased and there were no significant changes in b* values. The researchers attributed the decrease in a* value to the myoglobin content affected by increased oxidation.

The effects of RF applications on properties of meat and meat products may vary depending on the RF application parameters such as frequency used, power, application time and also the characteristics and composition of the meat and meat product. Therefore, it is crucial to ascertain the specific conditions associated with each product and to implement the appropriate RF parameters.

5. Future Perspectives

The RF technology has been proven as a safe and effective method for various food products and has potential to replace traditional methods in the industry. Studies showed that RF system is successful to protect nutritional and beneficial components of foods after treatment. It has advantages like rapid heating and short processing time. Some studies have indicated that RF method is more effective than conventional techniques in enhancing the organoleptic characteristics of food products.

Current studies have proven that RF is a promising technology for animal origin food products and RF systems are safe and efficient for the following purposes: thawing meat and seafood products, tempering meat, heating ready-to-eat foods, pasteurize animal-origin foods, and sterilizing/pasteurizing in-package. A variety of combination technology trials are conducted with diverse systems with the objective of enhance the impact of the system on the foods. Recent studies support the exploration of combined RF systems, such as radiofrequency-assisted cryogenic freezing. Quality characteristics of products following the application of radio frequency (RF) treatment, the effects of disparate geometries and the influence of different pre-applications are also subjecting of current research.

However, it was clear that the RF system has its own limitations. Even though this technology has been available for many years, its total adaptation to industry is relatively slow. One of the limitations is nonuniformity heating capacity especially for small-irregular shapes. There are not enough studies to determine dielectric properties of a variety of foods. Based on the parameters, there is a possibility that certain meat or meat product textures may deviate from the norm. Future studies should focus on exploring different methods and combinations to design a proper RF system. Further investigation is required to ascertain the impact of RF treatment on the quality and sensory properties of the products. To conclude, while the RF system presents certain limitations, its potential benefits shows its promising future applications in both domestic and industrial area.

Conflict of Interest

The authors declare no conflict of interest.

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