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Optimization of Value-Added Flavoured Milk Formulation Incorporating Spirulina Powder for Enhanced Functional Properties

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Abstract: The development of functional dairy beverages has increasingly focused on incorporating nutrient-dense ingredients capable of improving the nutritional and physiological value of conventional products. Spirulina powder represents a promising functional ingredient because of its protein, essential amino acid, pigment, mineral, and bioactive constituent profile. The present research develops an analytical formulation framework for optimizing value-added flavoured milk containing Spirulina powder, with emphasis on nutritional functionality, physicochemical characteristics, sensory acceptability, and product stability. The proposed methodology integrates controlled Spirulina incorporation with evaluation of pH, titratable acidity, protein content, functional properties, lipid-related nutritional attributes, and sensory quality. Particular attention is given to the concentration-dependent trade-off between enhanced nutritional functionality and consumer acceptability. Existing evidence indicates that Spirulina can contribute nutritionally important amino acids, minerals, and gamma-linolenic acid, while its incorporation into milk-based products can be technically feasible when formulation and processing conditions are appropriately controlled. The analytical framework further recognizes the importance of milk-protein interactions and thermal behavior in determining beverage stability. Rather than reporting fabricated experimental measurements, the Results section presents literature-grounded formulation findings and an optimization interpretation derived exclusively from the supplied references. The study establishes a systematic basis for developing Spirulina-enriched flavoured milk while identifying sensory intensity, processing stability, and concentration optimization as major formulation constraints. The proposed approach can support future experimental validation and development of commercially acceptable functional dairy beverages.

Keywords: Spirulina powder, functional milk, flavoured milk, formulation optimization, functional food, dairy beverage, nutritional enrichment, sensory acceptability, protein functionality.

1. Introduction:

The increasing interest in functional foods has encouraged food researchers to redesign conventional products so that they provide benefits beyond basic nutrient supply. Milk is particularly suitable for functional-food development because it possesses a nutritionally valuable protein matrix, is widely consumed, and can accommodate additional ingredients through controlled formulation. Flavoured milk provides an additional opportunity because flavouring can potentially moderate the sensory impact of nutritionally dense ingredients while maintaining consumer familiarity.

Spirulina is of particular interest as a functional ingredient because its nutritional composition includes proteins, amino acids, minerals, pigments, and biologically relevant fatty acids. Fatima and Srivastava (2017) discussed the presence and importance of essential amino acids in Spirulina, while Janda-Milczarek et al. (2023) identified Spirulina supplements as a potential source of mineral nutrients. Choopani et al. (2016) further emphasized Spirulina as a source of gamma-linolenic acid and examined its applications. These characteristics provide a theoretical basis for incorporating Spirulina into a conventional dairy matrix.

The functional rationale extends beyond protein and mineral enrichment. Fatty acids have important physiological roles, and the broader nutritional significance of polyunsaturated fatty acids has been discussed in relation to human development and physiological processes (Das, 2003; Innis, 2008). Calder (2015) particularly highlighted the biological relevance of marine omega-3 fatty acids and their involvement in inflammatory processes, emphasizing that lipid composition should be considered not merely as a compositional characteristic but in relation to potential physiological relevance. Although Spirulina-based milk should not automatically be equated with an omega-3-enriched product, the nutritional discussion demonstrates why lipid-related functionality can be considered within a broader functional-food framework (Calder, 2015).

However, nutritional enrichment does not automatically produce a successful food product. Increasing the concentration of a functional ingredient may alter colour, flavour, acidity, texture, dispersibility, and overall sensory acceptability. Boukhari et al. (2018) demonstrated that treatment conditions can influence the protein content and functional properties of Spirulina powder, indicating that the ingredient itself should be considered as a technologically active component rather than a simple nutrient additive.

The central problem, therefore, is one of formulation optimization: how can Spirulina be incorporated into flavoured milk at a level sufficient to enhance functional characteristics without compromising physicochemical stability and sensory quality? The objective of this study is to establish an analytical framework for such optimization. The scope includes ingredient functionality, formulation strategy, processing considerations, physicochemical evaluation, sensory assessment, and interpretation of the expected relationships between Spirulina concentration and product quality.

The significance of this approach lies in integrating nutritional and technological considerations rather than treating functional enrichment as an isolated compositional modification. Such integration is essential because the commercial value of a functional dairy beverage ultimately depends on achieving an acceptable balance between nutritional enhancement, stability, processing feasibility, and consumer acceptance.

2. LITERATURE REVIEW

2.1 Nutritional and Functional Basis of Spirulina

The nutritional suitability of Spirulina for functional-food formulation is supported by its protein and amino-acid composition. Fatima and Srivastava (2017) specifically examined essential amino acids in Spirulina, providing a basis for considering the microalgal powder as a protein-oriented functional ingredient. The significance of amino acids is particularly relevant when Spirulina is incorporated into milk because the resulting formulation combines the nutritional characteristics of the dairy matrix with those of the microalgal ingredient.

Spirulina also represents a source of minerals. Janda-Milczarek et al. (2023) examined Spirulina supplementation as a source of mineral nutrients, supporting its consideration in nutritional enrichment strategies. Nevertheless, mineral contribution should be interpreted according to actual formulation concentration and bioavailability rather than assuming that the presence of minerals automatically translates into a proportional physiological benefit.

Choopani et al. (2016) identified Spirulina as a source of gamma-linolenic acid and discussed its applications. This lipid component adds another dimension to Spirulina functionality. The broader importance of dietary polyunsaturated fatty acids is established in studies concerning brain development and physiological function (Das, 2003; Innis, 2008). Calder (2015) further demonstrated the importance of understanding fatty acids through their biochemical and inflammatory relevance rather than merely their quantitative concentration. Consequently, a Spirulina-enriched dairy beverage may be conceptualized as a multifunctional food system in which protein, mineral, pigment, and lipid-related properties coexist.

2.2 Functional and Technological Properties

The effectiveness of Spirulina in a dairy formulation depends partly on its technological properties. Boukhari et al. (2018) investigated ultrasound treatment and reported effects on protein content and functional properties of Spirulina powder. This finding is relevant because ingredient functionality can influence dispersion, interaction with milk proteins, and final beverage structure.

The interaction between Spirulina constituents and milk proteins also requires consideration of thermal processing. de Wit and Swinkels (1980) examined the thermal denaturation behavior of bovine β-lactoglobulin, demonstrating that milk proteins undergo temperature-dependent structural changes.

For a Spirulina-containing beverage, thermal treatment must therefore be evaluated not only from a microbiological perspective but also in terms of its potential effect on protein structure and product stability.

Microencapsulation provides another technological strategy. De Oliveira et al. (2021) investigated microencapsulation of Spirulina sp. LEB-18 and its incorporation into chocolate milk, reporting properties and functional potential of the resulting system. This study is particularly relevant to the present research direction because it demonstrates the feasibility of integrating Spirulina-derived material into a milk-based beverage while addressing technological issues associated with direct incorporation.

2.3 Sensory and Physicochemical Considerations

Flavoured milk optimization requires control of acidity and sensory balance. Amerine et al. (1965) demonstrated the relationship between pH, titratable acidity, and acid taste, establishing a theoretical foundation for considering acidity as a sensory as well as physicochemical parameter. This is important because alterations associated with Spirulina addition could influence the perceived balance of the beverage.

The microbiological quality of the final product is equally important. Harrigan (1998) and Harrigan and McCance (1976) provide methodological foundations for laboratory evaluation of food and dairy microbiology. Therefore, any experimentally validated Spirulina milk formulation should include microbiological assessment as part of quality and safety evaluation.

2.4 Research Gap

The supplied literature establishes separate foundations for Spirulina nutrition, amino-acid contribution, mineral value, lipid functionality, technological treatment, milk-protein behavior, and dairy-product incorporation. However, a clear formulation framework connecting these dimensions into an integrated optimization strategy remains limited within the supplied references. The present study addresses this conceptual gap by treating Spirulina concentration as a controllable formulation variable whose success must be evaluated through multiple response variables.

The theoretical position of the study is consequently based on a multi-objective optimization model: nutritional functionality should be increased, while undesirable changes in sensory quality, physicochemical stability, and processing performance should be minimized. Calder (2015) reinforces the importance of interpreting nutritional functionality within a broader biological framework, while the technological studies demonstrate that functional ingredients must also perform satisfactorily within the food matrix (Calder, 2015; Boukhari et al., 2018).

3. METHODOLOGY

3.1 Research Design

The study adopts a formulation-optimization framework for developing Spirulina-enriched flavoured milk. Because no experimental dataset was supplied with the research brief, the present paper does not invent numerical observations or claim experimentally measured values. Instead, the methodology specifies a reproducible experimental design and the Results section reports literature-grounded formulation findings and analytical expectations.

The independent formulation variable is Spirulina powder concentration. The principal dependent variables are nutritional composition, protein-related functionality, pH, titratable acidity, sensory acceptability, colour, beverage homogeneity, and microbiological quality. A control formulation without Spirulina should be maintained to establish a baseline for comparison.

A practical experimental design would include a control and several progressively enriched treatments. For example, formulations could be organized from a zero-Spirulina control to low, intermediate, and higher incorporation levels. The exact concentration range should be established through preliminary trials rather than arbitrarily fixed because Spirulina quality, particle characteristics, flavour system, and milk composition can influence the optimum level.

3.2 Raw Material Preparation

Food-grade Spirulina powder should be subjected to appropriate preliminary quality assessment before incorporation. Parameters should include appearance, odour, moisture-related quality, dispersibility, and microbiological suitability. The technological characteristics of the powder are important because treatment can modify its protein content and functional behavior (Boukhari et al., 2018).

Milk should be standardized according to the intended formulation. A selected flavouring system and sweetening strategy should be held constant across treatments so that differences can be primarily attributed to Spirulina incorporation. This experimental control is essential for distinguishing the nutritional ingredient effect from changes caused by other formulation components.

3.3 Formulation and Processing Framework

The proposed process consists of milk standardization, pre-dispersion of Spirulina, controlled mixing, flavour incorporation, homogenization or equivalent dispersion treatment, heat processing, cooling, filling, and refrigerated storage.

Pre-dispersion is particularly important because direct addition of dry powder may produce agglomeration and non-uniform distribution. A controlled dispersion stage can improve contact between Spirulina particles and the milk matrix. If advanced processing is employed, treatment conditions should be selected with consideration of the functional characteristics of Spirulina identified by Boukhari et al. (2018).

Thermal processing requires special attention because milk proteins undergo structural transitions during heating. The thermal behavior of β-lactoglobulin documented by de Wit and Swinkels (1980) provides a theoretical basis for monitoring processing conditions. Excessive thermal exposure could modify protein interactions and consequently influence viscosity, stability, or sensory properties.

3.4 Physicochemical Evaluation

The pH and titratable acidity of each formulation should be measured using standardized laboratory procedures. These measurements are complementary: pH reflects hydrogen-ion activity, whereas titratable acidity estimates the total acid-neutralizing requirement. Their relationship is relevant to flavour perception, as demonstrated by Amerine et al. (1965).

Protein content should be determined using an appropriate validated analytical procedure. Lipid analysis may be performed when the study specifically evaluates fatty-acid-related functionality. Iverson et al. (2001) compared Bligh and Dyer and Folch methods for total lipid determination in marine tissues, providing methodological context for lipid extraction. The selected method should be appropriate for the dairy-microalgal matrix.

Functional evaluation should include dispersibility, phase separation, sedimentation, and storage stability. These parameters are necessary because nutritional enhancement is of limited practical value if the beverage develops unacceptable physical instability.

3.5 Sensory Evaluation

Sensory evaluation should assess colour, flavour, aroma, mouthfeel, sweetness, aftertaste, and overall acceptability. A structured hedonic scale can be used with an appropriate panel. The principal analytical objective is to determine whether increasing Spirulina concentration creates a nonlinear decline in acceptability.

This is especially important because Spirulina may introduce distinctive colour and flavour characteristics. The formulation challenge is therefore not simply to maximize Spirulina concentration but to identify the highest level that remains technologically and sensorially acceptable.

3.6 Microbiological Assessment

Microbiological quality should be evaluated using recognized food and dairy microbiological procedures. Harrigan (1998) and Harrigan and McCance (1976) provide foundational methodological references for laboratory assessment of food and dairy microbiology. Total viable counts and relevant indicator organisms should be monitored according to applicable laboratory and regulatory procedures.

3.7 Optimization Model

A multi-response desirability framework can be applied to identify the optimum formulation. Nutritional parameters such as protein and mineral contribution should be maximized, while undesirable responses such as excessive acidity, phase separation, sedimentation, or poor sensory scores should be minimized.

Conceptually, the overall formulation objective can be represented as:

Overall desirability = f(nutritional functionality, physicochemical stability, sensory acceptability, and microbiological quality).

The optimum is therefore not necessarily the treatment containing the maximum amount of Spirulina. Instead, it is the formulation at which the marginal nutritional advantage of additional Spirulina is balanced against sensory and technological penalties.

4. RESULTS

The literature-grounded analysis indicates that Spirulina is technically suitable for consideration as a functional enrichment ingredient in flavoured milk, but the optimum formulation should be determined through multi-response evaluation rather than nutritional composition alone. The principal expected benefit is enrichment of the beverage with protein-associated nutrients, essential amino acids, minerals, and selected bioactive components. Evidence concerning essential amino acids supports the protein-oriented rationale for incorporation (Fatima & Srivastava, 2017), while mineral-focused evidence supports its potential contribution to dietary mineral intake (Janda-Milczarek et al., 2023).

A second finding is that Spirulina concentration should be treated as an optimization variable rather than an unconditional quality enhancer. Boukhari et al. (2018) demonstrated that Spirulina powder possesses measurable functional characteristics that can be affected by processing. Consequently, the physical behavior of the ingredient in milk may change with concentration, treatment, and dispersion conditions. A higher inclusion level can theoretically increase nutritional density while simultaneously increasing the probability of colour intensification, characteristic flavour development, sedimentation, or altered mouthfeel.

The literature also indicates that processing conditions are central to formulation success. The thermal behavior of bovine β-lactoglobulin demonstrates why heat treatment must be controlled when developing milk-based functional beverages (de Wit & Swinkels, 1980). A formulation that provides strong nutritional enrichment but undergoes undesirable protein interactions or physical instability would not represent an optimized product.

From the sensory perspective, pH and titratable acidity require joint monitoring. Amerine et al. (1965) established that pH and titratable acidity influence acid taste, meaning that physicochemical measurements cannot be interpreted independently from sensory response. Accordingly, a successful flavoured milk formulation should maintain an acceptable sensory balance while accommodating the functional ingredient.

The supplied literature also supports the possibility of improving technological incorporation through processing approaches. De Oliveira et al. (2021) demonstrated the incorporation of microencapsulated Spirulina into chocolate milk, indicating that technological modification can assist the integration of Spirulina into a dairy beverage. This provides a useful pathway when direct powder incorporation produces unacceptable sensory or physical effects.

The lipid-related interpretation should remain scientifically cautious. Spirulina-derived fatty acids can contribute to the functional profile of the formulation, and the broader physiological relevance of polyunsaturated fatty acids is well established (Das, 2003; Innis, 2008). However, the presence of a particular fatty acid should not be interpreted as proof of a clinical benefit. Calder (2015) emphasized the mechanistic complexity of fatty-acid effects and inflammatory processes, reinforcing the need to distinguish nutritional composition from demonstrated health outcomes.

Overall, the findings support a formulation strategy in which an intermediate Spirulina concentration is likely to provide a more appropriate optimization target than maximum supplementation. This conclusion remains a hypothesis requiring experimental validation rather than a claim of a measured optimum.

5. DISCUSSION

The central implication of the analysis is that successful Spirulina-flavoured milk development should be understood as a balance between nutritional enrichment and product functionality. A purely compositional approach would favor increasing Spirulina concentration because greater inclusion can potentially increase the contribution of protein, minerals, amino acids, and bioactive constituents. However, the food product must also remain acceptable to consumers and stable throughout processing and storage.

The technological evidence provides an important explanation for this trade-off. Spirulina is not an inert powder; its functional properties can be influenced by treatment conditions (Boukhari et al., 2018). Consequently, dispersion and processing become integral parts of formulation optimization. The use of appropriate processing technologies, including encapsulation where necessary, may reduce some of the disadvantages associated with direct addition. The incorporation of microencapsulated Spirulina into chocolate milk reported by De Oliveira et al. (2021) supports the feasibility of this technological direction.

Protein interactions provide another important consideration. Milk proteins respond to thermal conditions, and β-lactoglobulin exhibits defined thermal denaturation behavior (de Wit & Swinkels, 1980). Since Spirulina also contains substantial proteinaceous material, the final product represents a complex mixed-protein system. This interaction may influence viscosity, dispersion, stability, and mouthfeel. Therefore, the optimization model should incorporate processing conditions rather than treating ingredient concentration as the only independent variable.

Nutritional interpretation should also remain appropriately conservative. Spirulina's amino-acid and mineral contributions support its classification as a nutritionally valuable ingredient (Fatima & Srivastava, 2017; Janda-Milczarek et al., 2023). Its gamma-linolenic acid content provides an additional functional dimension (Choopani et al., 2016). Nevertheless, nutritional presence does not establish clinical efficacy. Calder (2015) illustrates why fatty-acid functionality must be interpreted through biochemical mechanisms and physiological context rather than simple nutrient labeling. Thus, the proposed beverage should be described as a potentially functional food rather than as a therapeutic product.

The sensory dimension is likely to represent the strongest practical limitation. Even when nutritional functionality increases, consumer acceptance may decline if the characteristic colour, aroma, or taste of Spirulina becomes dominant. Flavouring can potentially improve palatability, but this should be empirically established rather than assumed. Acidity control is particularly relevant because pH and titratable acidity contribute to perceived taste (Amerine et al., 1965).

Microbiological stability must likewise remain an essential criterion. The use of established food and dairy microbiological methods is necessary to verify product safety and storage quality (Harrigan, 1998; Harrigan & McCance, 1976). Nutritional and sensory optimization without microbiological validation would be incomplete.

From a theoretical perspective, the study contributes a multi-dimensional model for functional dairy formulation. The optimization target is defined not by maximum Spirulina inclusion but by the point at which nutritional gains, sensory acceptance, physicochemical stability, and processing feasibility converge. This model is particularly appropriate for functional foods because increasing one desirable property can simultaneously create undesirable changes elsewhere.

The principal limitation of the present paper is the absence of primary experimental measurements. Therefore, the identified optimum cannot be assigned a numerical Spirulina concentration without laboratory validation. Future research should experimentally compare multiple inclusion levels, evaluate storage stability, quantify nutrient retention after processing, conduct statistically powered sensory trials, and examine the interaction between Spirulina constituents and milk proteins. Lipid profiling may additionally clarify the contribution of Spirulina-derived fatty acids, while mechanistic interpretation should remain consistent with the broader evidence concerning fatty-acid functionality (Calder, 2015).

6. CONCLUSION

The optimization of Spirulina-enriched flavoured milk requires an integrated approach combining nutritional enhancement, technological functionality, sensory acceptability, physicochemical stability, and microbiological quality. The supplied literature establishes a strong rationale for Spirulina incorporation because of its protein and amino-acid characteristics, mineral contribution, and selected lipid-related functionality. At the same time, evidence concerning Spirulina processing and milk-protein behavior demonstrates that formulation and processing conditions can substantially influence the final product.

The proposed optimization framework therefore recommends identifying a balanced inclusion level rather than maximizing Spirulina concentration. Such an approach recognizes that a successful functional beverage must deliver nutritional value without unacceptable changes in flavour, colour, texture, acidity, or physical stability. Encapsulation and controlled dispersion represent promising technological strategies where direct incorporation creates formulation difficulties.

Importantly, the present study does not fabricate experimental measurements. The proposed optimum should consequently be regarded as an experimentally testable formulation hypothesis. Future laboratory investigations should validate concentration-response relationships, determine the statistically optimal formulation, evaluate refrigerated shelf life, quantify nutritional retention, and establish consumer acceptability. With such validation, Spirulina-enriched flavoured milk could provide a scientifically grounded pathway for developing nutritionally enhanced and technologically viable functional dairy beverages.

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