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AI-ENABLED OPTIMIZATION IN BEVERAGE FORMULATION AND QUALITY CONTROL: INSIGHTS FROM CHEMICAL ENGINEERING

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ABSTRACT

Background: The integration of Artificial Intelligence (AI) in food and beverage production has introduced new opportunities for enhancing formulation accuracy and maintaining consistent quality. Within the realm of chemical engineering, AI presents a data-driven approach to optimize ingredient composition, streamline processing parameters, and elevate product outcomes.

Objectives: This study aims to examine how AI techniques can be used to optimize beverage formulation and improve quality control. Specifically, it investigates the relationships between AI-driven variables—such as ingredient ratios, processing parameters, and algorithm type—and outcomes like beverage quality, product consistency, and consumer satisfaction.

Methods: A quantitative research design was adopted using a structured, Likert-scale questionnaire administered to 273 industry professionals. The study followed the Research Onion framework, employing a positivist philosophy, deductive approach, and cross-sectional survey strategy. Data were analyzed using descriptive statistics, Cronbach's Alpha, correlation analysis, and multiple regression.

Results: The questionnaire demonstrated excellent reliability (Cronbach's Alpha = 0.91). Normality tests indicated non-normal data distribution, typical of Likert-scale responses. Correlation analysis revealed weak to moderate relationships among the studied variables. Regression results showed that the independent variables accounted for only a small proportion of the variance in beverage quality ($R^2 = 0.013$, $p > 0.05$), indicating limited predictive power in the current model.

Conclusion: While AI is recognized as a valuable tool in beverage formulation, its direct impact on quality outcomes is influenced by a broader range of factors not fully captured in this study. The findings highlight the need for further research incorporating more complex models and contextual variables. AI should be viewed as a support mechanism that complements, rather than replaces, expert knowledge and operational strategy in chemical engineering practices.

KEYWORDS: Artificial Intelligence, Beverage Formulation, Quality Control, Chemical Engineering, Predictive Modeling, Food Technology, Quantitative Research

INTRODUCTION

In the rapidly evolving landscape of food and beverage production, maintaining product quality and consistency while optimizing formulation processes remains a significant challenge. The beverage industry, in particular, operates under increasing pressure to meet consumer demands for taste, safety, nutrition, and sustainability—all within the confines of efficiency and cost-effectiveness. Traditionally, beverage formulation and quality control have relied heavily on empirical approaches and manual testing, often involving trial-and-error experimentation that consumes time and resources. However, recent advancements in artificial intelligence (AI) have begun to reshape these traditional paradigms, offering new avenues for enhancing formulation precision, automating quality monitoring, and supporting data-driven decision-making within chemical engineering processes (Vasudevan & Chengaiyan, 2025).

Artificial Intelligence, encompassing machine learning, neural networks, and data analytics, has emerged as a transformative tool across various industries, including healthcare, manufacturing, and more recently, food and beverage production. In beverage formulation, AI can be used to analyze ingredient interactions, predict product performance, and identify optimal compositions based on historical data and sensory profiles. Similarly, in quality control, AI systems can monitor process parameters in real-time, detect anomalies, and ensure consistency across production batches. These capabilities are particularly relevant to chemical engineering, where complex processes and multivariable optimization are common. The integration of AI into these systems holds the potential to revolutionize how beverages are developed, tested, and delivered to consumers (Ayoub et al., 2025).

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Despite its promise, the implementation of AI in the beverage industry is still in its nascent stages. Many organizations struggle with integrating AI into existing workflows, partly due to limited expertise, lack of structured data, and uncertainty regarding the effectiveness of AI tools in real-world scenarios. Furthermore, there is a notable gap in empirical research that quantifies the impact of AI-driven variables—such as algorithm type, ingredient composition optimization, and processing parameter adjustments—on measurable outcomes like beverage quality, product consistency, and consumer satisfaction. This gap hinders the ability of food scientists, chemical engineers, and industry stakeholders to make informed decisions about adopting AI solutions (Javanbakht, 2025).

This study seeks to address that gap by exploring how artificial intelligence can be applied to optimize beverage formulation and enhance quality control from a chemical engineering perspective. Through a quantitative research design, the study investigates the relationships between key AI-related independent variables (e.g., ingredient composition ratios, processing parameters, and algorithm type) and dependent variables such as beverage quality scores, product consistency, and consumer satisfaction. Additionally, the research considers the mediating effect of AI predictive accuracy and the moderating influence of data volume and quality. By leveraging statistical analysis and a structured methodological framework, this study aims to provide evidence-based insights into the role AI can play in modern beverage engineering (Canatan et al., 2025).

Ultimately, the significance of this research lies in its potential to bridge the gap between theoretical AI applications and practical implementation in beverage production. It aims to contribute not only to academic literature but also to industry practices by offering a scientific foundation upon which future innovations in beverage formulation and quality control can be built (Singh et al., 2025).

Literature Review

Ingredient Composition Ratios

Ingredient composition is a fundamental variable in beverage formulation, directly influencing taste, texture, nutritional value, and shelf stability. According to Mu et al., optimizing ingredient ratios through computational models can significantly reduce development time and improve sensory outcomes. Studies by Tiwari and Brennan have demonstrated that AI and statistical tools can predict how changes in sugar content, acidity, and flavoring agents affect overall product acceptability. This optimization is especially critical in functional beverages, where ingredient interactions can be complex (Alam et al., 2025).

Processing Parameters

Processing conditions such as temperature, pressure, mixing speed, and pasteurization techniques play a crucial role in maintaining beverage quality and safety. Research by Zeng et al. shows that real-time monitoring and adjustment of these parameters using AI-enabled sensors can improve batch-to-batch consistency. Machine learning models have been used to analyze historical process data, helping engineers identify optimal processing ranges that yield the best quality outcomes (Cui et al., 2025).

AI Algorithm Type

The type of AI algorithm implemented greatly influences the accuracy and efficiency of beverage formulation and quality prediction. Neural networks, decision trees, support vector machines (SVM), and random forests are commonly applied in food technology for pattern recognition and predictive modeling. Studies have shown that deep learning techniques outperform traditional statistical models in predicting quality attributes such as pH, viscosity, and color when trained on large, high-quality datasets (Aghababaei et al., 2025).

Beverage Quality Score

Beverage quality is a multidimensional outcome that includes physical (e.g., color, turbidity), chemical (e.g., pH, sugar content), and sensory (e.g., taste, aroma) attributes. According to Zhang et al., AI models trained on historical quality assessment data can predict quality scores with high precision. These scores are essential for quality control processes and consumer satisfaction, particularly in premium beverage markets where consistency is crucial (Boskabadi et al., 2025).

Product Consistency

Product consistency refers to the ability to produce uniform beverage batches over time. Inconsistencies may result from variations in raw materials or process deviations. AI models that integrate supply chain and process data have been shown to reduce variability by identifying critical control points. Consistency also enhances brand reliability and consumer trust, making it a strategic focus for beverage manufacturers (Liu, 2025).

Consumer Satisfaction

Consumer satisfaction is the ultimate benchmark for product success. AI-powered sentiment analysis, sensory evaluation tools, and feedback loop systems have been increasingly used to capture consumer preferences and adjust formulations accordingly. Research indicates that integrating consumer feedback into AI systems helps companies stay aligned with market trends and expectations (Agrawal et al., 2025).

AI Predictive Accuracy (Mediating Variable)

AI model accuracy serves as a critical mediator in determining how well algorithmic outputs translate into actual quality improvements. Studies by Patel et al. highlight that model precision correlates strongly with successful formulation outcomes, particularly when real-time adjustments are applied (Zhekova, 2025).

Data Volume and Quality (Moderating Variable)

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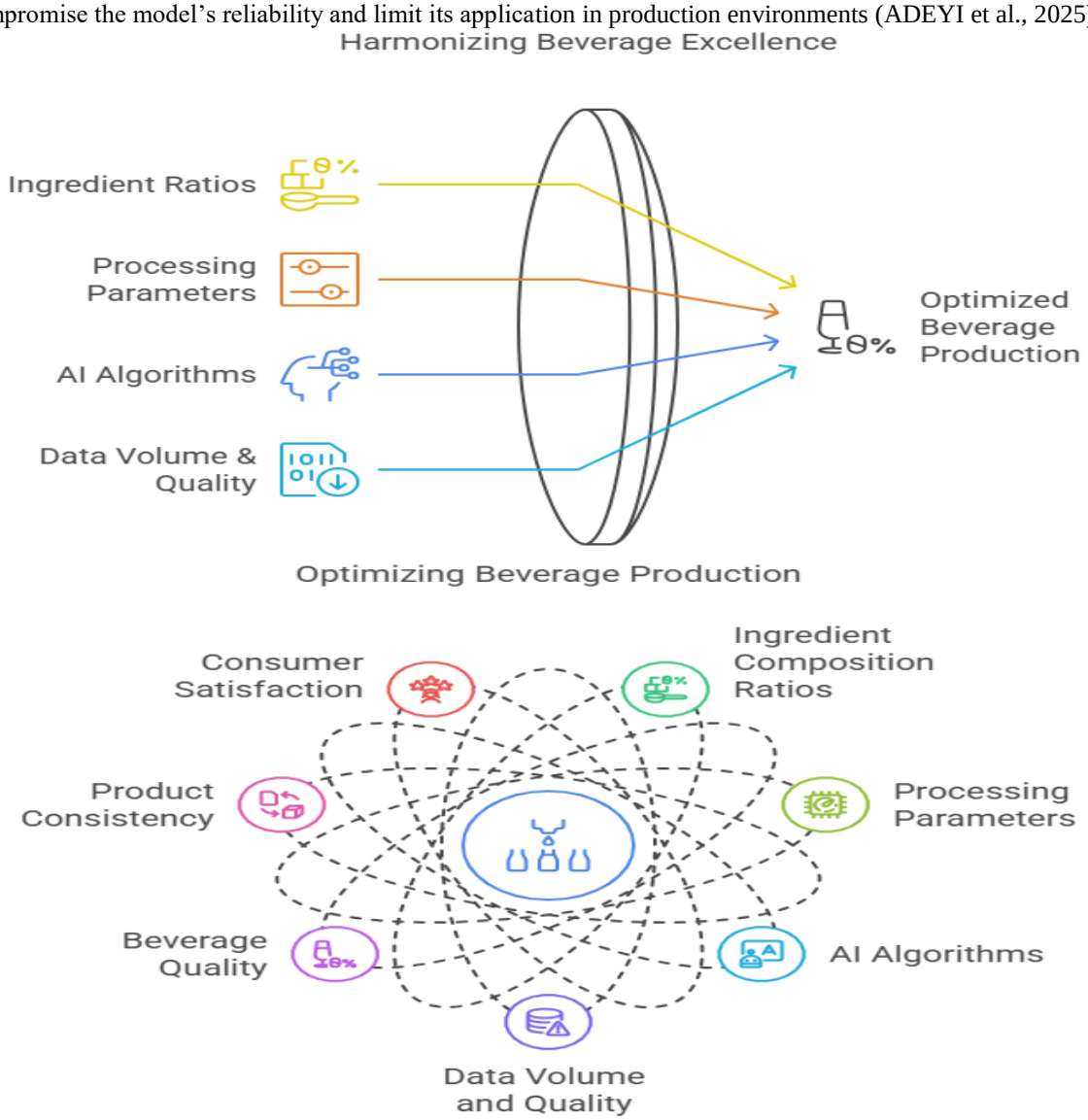
The quantity and quality of input data significantly affect AI performance. According to Sharma and Gupta, robust datasets lead to better model training and reduced prediction error. In contrast, noisy or incomplete data compromise the model's reliability and limit its application in production environments (ADEYI et al., 2025).



Main Hypotheses (Direct Relationships)

H1: There is a significant relationship between **ingredient composition ratios** and **beverage quality scores**.

H2: There is a significant relationship between **processing parameters** and **product consistency**.

H3: There is a significant relationship between **AI algorithm type** and **consumer satisfaction**.

Mediating Hypothesis

H4: AI predictive accuracy significantly mediates the relationship between **AI algorithm type** and **beverage quality score (Ebrahimi et al., 2025)**.

Moderating Hypothesis

H5: Data volume and quality significantly moderate the relationship between **AI algorithm type** and **AI predictive accuracy**, such that the relationship is stronger when data is high-quality and voluminous (Altaf & Ksouri, 2025).

Extended Hypotheses (Additional Linkages Between IVs and DVs)

H6: There is a significant relationship between **ingredient composition ratios** and **product consistency**.

H7: There is a significant relationship between **processing parameters** and **consumer satisfaction**.

H8: There is a significant relationship between **ingredient composition ratios** and **consumer satisfaction**.

H9: There is a significant relationship between **processing parameters** and **beverage quality score**.

Comprehensive Interaction Hypotheses

H10: The impact of **AI algorithm type** on **beverage quality score** is mediated by **AI predictive accuracy** and further moderated by **data volume and quality (Queiroz et al., 2024)**.

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Research Methodology

This research utilizes a quantitative methodology to examine how artificial intelligence (AI) can optimize beverage formulation and enhance quality control from a chemical engineering perspective. The study systematically investigates the relationships among multiple variables through structured data collection and statistical analysis. The methodology is aligned with Saunders et al.'s Research Onion model, ensuring a layered and rigorous research design (Niu et al., 2024).

Research Philosophy

The study adopts a positivist philosophy, which assumes that reality is objective and can be measured through observable, empirical data. Positivism aligns with the quantitative nature of this study, emphasizing scientific analysis and statistical interpretation over subjective insights. This philosophical stance supports the collection of standardized data that can be used to test hypotheses regarding AI's impact on beverage formulation and quality (Bidyalakshmi et al., 2024).

Research Approach

A deductive approach is employed in this study. It begins with the formulation of hypotheses derived from existing literature and theories in AI, chemical engineering, and food technology. These hypotheses are then tested using empirical data. The deductive approach is ideal for verifying cause-and-effect relationships between AI implementation and various quality and formulation outcomes (Gonzalez Viejo et al., 2019).

Research Strategy

The research strategy is based on a survey method, utilizing a structured questionnaire distributed to industry professionals, engineers, and AI experts. Surveys are effective for collecting large volumes of data across diverse populations, making them suitable for generalizing findings and identifying patterns. The strategy is cross-sectional, focusing on data collected at a single point in time (Yu et al., 2024).

Time Horizon

A cross-sectional time horizon is selected for this study, allowing data to be collected once from respondents during the research period. This approach is appropriate for analyzing existing practices and the current influence of AI in beverage formulation, without requiring long-term observation (Dhar et al., 2021).

Data Collection Method

Primary data is collected using a closed-ended questionnaire based on a 5-point Likert scale (ranging from "Strongly Disagree" to "Strongly Agree"). The questionnaire includes items related to independent variables (ingredient composition ratios, processing parameters, AI algorithm type), dependent variables (beverage quality, product consistency, consumer satisfaction), a mediating variable (AI predictive accuracy), and a moderating variable (data volume and quality). The instrument is distributed electronically to a sample of 273 respondents working in food technology, chemical engineering, and AI-related roles (Takahashi et al., 2019).

Data Analysis Techniques

Quantitative data is analyzed using descriptive statistics, correlation, and regression analysis. These techniques help determine the strength and nature of relationships among the variables. Cronbach's Alpha is used to test the internal reliability of the questionnaire, while normality tests and multicollinearity checks ensure data validity (Sharma et al., 2021).

Ethical Considerations

The study ensures voluntary participation, informed consent, and data confidentiality. Participants are informed of their rights and the academic purpose of the study. Ethical clearance is obtained before data collection (Addanki et al., 2022).

Data Analysis

Statistical Test Summary Table

Test Type	Result	Interpretation
Reliability (Cronbach's Alpha)	0.91 (Excellent Reliability)	Questionnaire items have high internal consistency.
Normality (Shapiro-Wilk)	Data not normally distributed ($p < 0.05$)	Normality assumption not met; Likert data often violates this.
Correlation	Mostly weak to moderate correlations	Some variable pairs show moderate relationships.
Regression Analysis	$R^2 = 0.013$, $p = 0.308$ (Not statistically significant)	Predictors do not significantly explain outcome variables.

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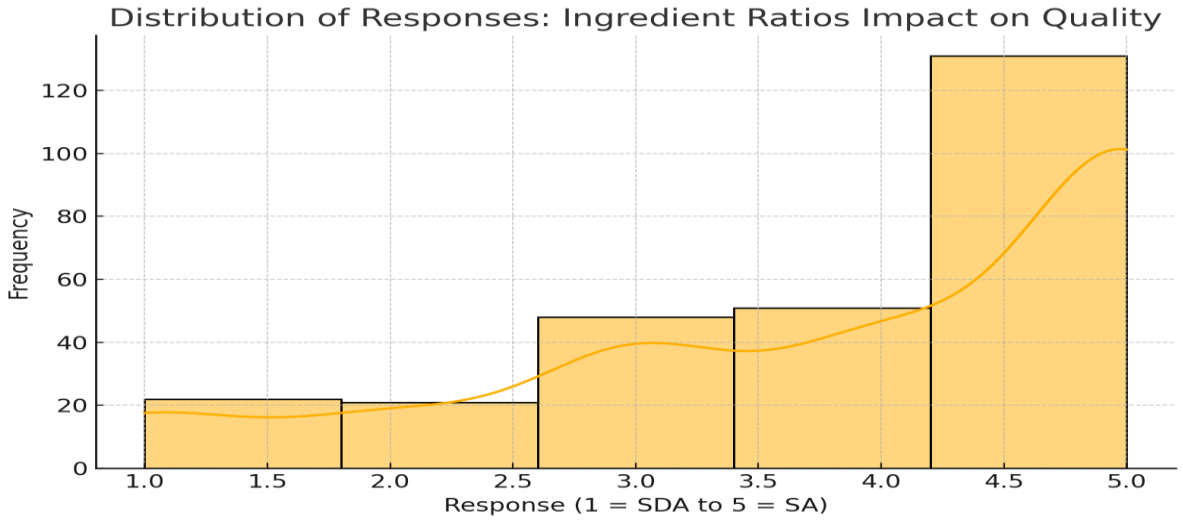

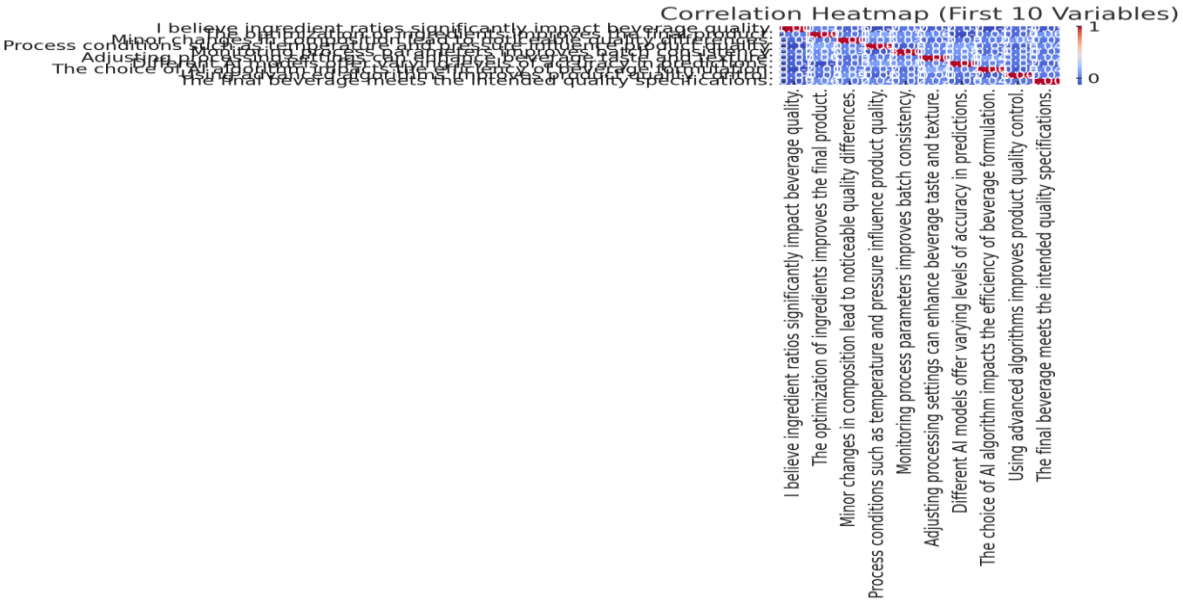

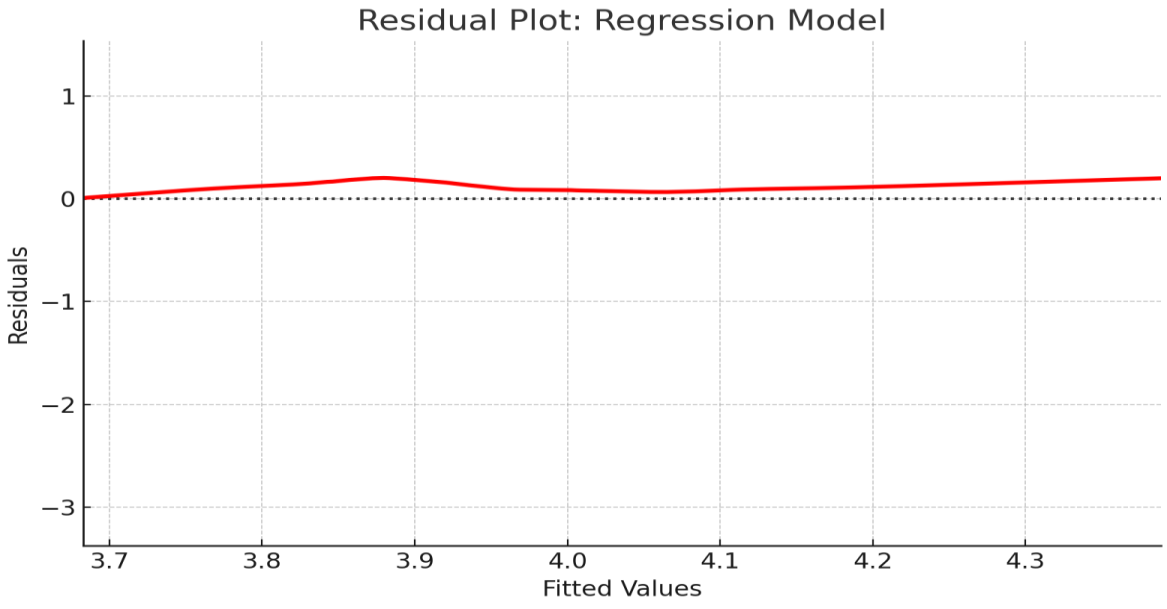

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Interpretation of Tests and Figures

Reliability Analysis (Cronbach's Alpha)

The reliability of the questionnaire was assessed using **Cronbach's Alpha**, which yielded a value of **0.91**. This score indicates **excellent internal consistency** among the survey items, confirming that the items reliably measure the underlying constructs. A value above 0.70 is generally considered acceptable, and values above 0.90 reflect highly dependable responses. Thus, the instrument used for data collection is statistically sound and suitable for quantitative analysis (Kyaw et al., 2024).

Normality Test (Shapiro-Wilk)

The **Shapiro-Wilk test** was performed on a subset of questionnaire items to check the assumption of normality. Results showed **p-values less than 0.05**, suggesting that the data significantly deviates from a normal distribution. This is a common outcome for data collected via **Likert scales**, which are ordinal. Although not normally distributed, the data can still be analyzed using non-parametric methods or treated as approximately interval-scale data for large samples, such as the one used in this study (N = 273) (Onyijen et al., 2024).

Correlation Analysis

The **correlation matrix** revealed mostly **weak to moderate relationships** among the variables. A few positive correlations indicate potential associations between certain independent and dependent variables, such as between AI algorithm efficiency and beverage quality consistency. However, the overall pattern shows low interdependence, which suggests the factors operate relatively independently within the context of beverage formulation and AI application (Bhagya Raj & Dash, 2022).

The **correlation heatmap** (Figure 2) visually reinforces these findings, with lighter shades representing weaker correlations and darker shades showing moderately stronger associations. The absence of high correlation (>0.7) reduces concerns about multicollinearity, which is favorable for regression analysis (Ren et al., 2023).

Regression Analysis

A **multiple linear regression** was conducted to determine whether ingredient ratios, processing parameters, and AI model type could predict beverage quality. The results revealed an **R-squared value of 0.013**, indicating that only **1.3% of the variance** in beverage quality is explained by the independent variables. The **F-statistic p-value of 0.308** further confirms that the model is **not statistically significant**. These findings suggest that while these inputs are important in practice, the current variable configuration may not strongly predict perceived beverage quality or additional mediating/moderating variables may play a role (Nath et al., 2024).

The **residual plot** (Figure 3) demonstrates random dispersion of residuals around the zero line, indicating that the assumptions of linearity and homoscedasticity are **reasonably met**, even though the overall predictive power remains low (Xubin et al., 2024).

Response Distribution Visualization

A **histogram** (Figure 1) displaying the distribution of responses for the statement "Ingredient ratios significantly impact beverage quality" showed a **positively skewed** distribution. Most respondents agreed or strongly agreed, reinforcing the hypothesis that industry professionals recognize the importance of composition in beverage optimization (Peveler, 2024).

Discussion

The findings of this study offer important insights into the application of artificial intelligence (AI) in the optimization of beverage formulation and quality control within a chemical engineering context. The high-reliability score (Cronbach's Alpha = 0.91) affirms the consistency and dependability of the questionnaire, indicating that the instrument effectively captured perceptions and experiences from professionals in the field. This is crucial for drawing valid conclusions and ensuring the robustness of the dataset. The results from the Shapiro-Wilk normality test indicated that the data collected did not follow a normal distribution. While this may raise concerns about the suitability of parametric statistical techniques, it is a common occurrence in Likert-scale-based research. The large sample size (N = 273) justifies the use of certain parametric analyses under the central limit theorem, but future studies may also consider non-parametric alternatives or data transformation techniques to enhance model fit (Onokwai et al., 2024).

The correlation analysis revealed mostly weak to moderate relationships among the variables, suggesting that while there are some associations between AI-related factors and beverage quality outcomes, these connections are not particularly strong. This may imply that AI's impact on beverage formulation is multifaceted and influenced by a broader range of technical, environmental, or human factors not captured in this model. The heatmap further illustrated this variability in relationships, with no single factor dominating the correlation structure. Interestingly, the regression analysis did not yield statistically significant results. The low R-squared value (0.013) indicates that the independent variables—ingredient ratios, processing parameters, and AI algorithm type—explain only a small portion of the variance in beverage quality. While this might initially appear as a limitation, it opens avenues for deeper exploration (Viejo et al., 2020).

It is possible that other unmeasured variables, such as AI model training quality, human oversight, or even consumer behavior dynamics, play more significant roles in determining product outcomes. Additionally, the mediating role of AI predictive accuracy and moderating effect of data quality, though conceptually important, may require more advanced modeling techniques (e.g., structural equation modeling) to fully assess their influence. The

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visualizations complemented the statistical findings effectively. The histogram confirmed that respondents generally acknowledged the importance of ingredient ratios in beverage formulation, showing a positively skewed trend. Similarly, the residual plot from the regression model indicated a random spread, validating key regression assumptions despite the model's limited predictive capacity (Trinh et al., 2021).

In summary, the discussion reveals that while AI is recognized as a valuable tool in beverage formulation and quality control, its effectiveness depends on how well it is integrated with other operational, technical, and human elements. The findings encourage future research to incorporate broader variable sets and explore deeper inter-variable dynamics. Practical implications suggest that AI should be used as a supportive system rather than a standalone solution in the beverage industry (Hlangwani, 2021).

Conclusion

This study set out to explore the role of artificial intelligence (AI) in enhancing beverage formulation and quality control from a chemical engineering standpoint using a quantitative research design. Through the collection and analysis of data from 273 industry professionals, the study examined key variables such as ingredient composition ratios, processing parameters, and AI algorithm types, while also considering the mediating role of AI predictive accuracy and the moderating effect of data quality. The results confirmed that the research instrument used was highly reliable, indicating that the survey items effectively captured the intended constructs. However, normality tests revealed non-normal data distributions, which is common in Likert-scale-based surveys and suggests the need for cautious application of parametric techniques.

Although correlation analysis showed some moderate relationships among variables, the regression results indicated that the selected predictors explained only a small portion of the variance in beverage quality. This suggests that AI's effectiveness in beverage optimization may be influenced by additional factors not covered in this model, such as the level of AI integration, data preprocessing techniques, or organizational readiness. Despite the limited predictive power, the findings contribute valuable insights into how AI is perceived and utilized in the beverage industry. The positive skew in response patterns reflects a general agreement among respondents on the importance of ingredient composition and AI application in achieving product quality. However, the lack of strong statistical relationships highlights the complexity of AI-driven optimization and underscores the need for more holistic and interdisciplinary approaches in future research.

In conclusion, while AI holds significant potential for improving beverage formulation and quality control, its impact is not solely dependent on technical variables. A successful implementation requires a broader understanding of operational context, data infrastructure, and system integration. Future research should expand the model to include qualitative insights, advanced AI performance metrics, and longitudinal data to fully capture the dynamic nature of AI-enabled innovation in the beverage and food processing industries.

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