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Integrating Quantitative Methods and Digital Sensors to Enhance Product Quality in the Gummy Candy Industry

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The quality of food products is essential for consumer safety and the perception of the product's value. In production processes, traditional quality control methods are often carried out retrospectively, limiting the possibility of immediately interventions and causing inefficiencies. The Industrial Internet of Things (IIoT) and machine learning offer an innovative approach, enabling real-time data collection and processing to optimize several parameters that influence the final product's quality. This study discusses how these technologies can be applied to the gummy candy sector, where variables such as ingredient quantity, temperature, moisture and viscosity are critical parameters. Their precise control ensures standard products that meet consumer expectations. Smart sensors and artificial vision systems, implemented along the production lines, enable continuous monitoring, while predictive algorithms identify and correct deviations from optimal parameters. The integration of these tools enhances product quality, reduces waste, and optimizes the production process, also supporting the development of new and innovative formulations. Moreover, improved traceability enables detailed monitoring of the entire production cycle, ensuring greater food safety, regulatory compliance, and a faster response to potential issues. Real time traceability also facilitates supply chain management, improving logistical efficiency and increasing consumer trust through greater transparency in the final product.

1. Introduction

The global gummy candy market is experiencing significant expansion, due to changes in consumer behaviour and continuous innovation in product offering (Tarahi et al., 2024), with forecasts indicating a total value of 53.5 USD billion by 2030, supported by a compound annual growth rate (CAGR) of 9.3 % (Polaris Marker research, 2024). This phenomenon is driven by the growing demand for products with healthier and more transparent formulations, such as candies with reduced sugar content, free of synthetic additives, and enriched with functional ingredients (Gunes et al., 2022). At the same time, there is an increasing trend in gummy dietary supplements, with the European supplement market expected to reach 4.2 USD billion by 2028 according to a report by Markets and Markets (2023). These dynamics highlight the urgency for the confectionery industry to innovate processes and formulations to keep up with new trends. Maintaining high-quality standards is essential to comply with regulations and market demands, but quality monitoring often occurs only at the end of production, limiting timely corrective actions. Parameter adjustments are mainly based on experience and fixed protocols, without dynamic real-time control. Even minor operational variations can compromise product quality, reproducibility, leading to waste, inefficiencies, and high costs. The integration of Industrial Internet of Things (IIoT) technologies and machine learning algorithms today offer an innovative and proactive approach to optimizing quality control (Dadhaneeya et al., 2023).
Thus, this work is aimed to describe an ideal digital based system applied to gummy candy operations, to discuss how the integration of quantitative methods and digital sensors can enhance product quality in the gummy candy industry.

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2. Operations for gummy candy production

Currently most confectionery gel products are prepared in the food industry via a multi-step batch process. This process consists of several stages, and a prolonged drying period (Burey et al., 2023), as depicted in figure 1. From the processing point of view, these stages involve mass and energy transfer, with the structural modification associated to the thermodynamics conditions of each stage. Raw materials are dosed, mixed, cooked; the cooked mix is then transferred to casting/moulding operation, and the shaped product is then aged, finished and packaged. The appearance, texture, and taste influence strongly the acceptability of a food product as gummy candy and guide consumers in their purchase. For this reason, is fundamental the strict control of technological parameters that affect these aspects of the product. Ingredient dosing, temperature, moisture, viscosity, and pH are essential to ensure proper gel formation and stability (Tirek et al., 2023). The texture of candies produced using the gelation technique is related to several factors, including the type and amount of hydrocolloid used, as well as the water content of the final product. A higher hydrocolloid content and reduced water lead to harder candies. On the other hand, reducing the hydrocolloid content results in a softer and less gummy texture. If the candy is too soft, the hydrocolloid concentration may be too low, the water content too high, or the choice of hydrocolloid may be incorrect (e.g., the bloom strength of the gelatine is too low) (Gunes et al., 2022). Also, kinetics of heating and cooling play a decisive role in defining the structural properties of the product. During the heating phase, uniform dissolution of gelling agents must be facilitated through precise temperature control, avoiding chemical degradation or unwanted alterations that could compromise the functional properties of the gel. The cooling phase is equally critical, as it directly influences molecular cross-linking and the formation of the gel's three-dimensional structure. Therefore, an optimized management of cooling kinetics is essential to achieve an ideal balance between texture and stability, ensuring the quality of the final product. The application of IIoT technologies along the entire production line, combined with artificial intelligence, enables real-time monitoring and regulation of these parameters, improving process reproducibility and ensuring high-quality standards while significantly reducing waste and operational costs. If anomalies are detected, the system can automatically adjust key parameters. Process data analysis, through predictive algorithms and machine learning models, allows for the identification of correlations between operational variables and product quality, providing strategic insights to optimize equipment settings and prevent non-conformities. The collected data can be used not only to improve existing formulations but also to develop new recipes with greater precision and efficiency. Additionally, artificial intelligence enables the predictive evaluation of the stability of new formulations, identifying potential issues related to texture and shelf life (Dadhaneeya et al., 2023). This provides companies with advantages in terms of investment and production time, allowing them to be more competitive and responsive to customer need.

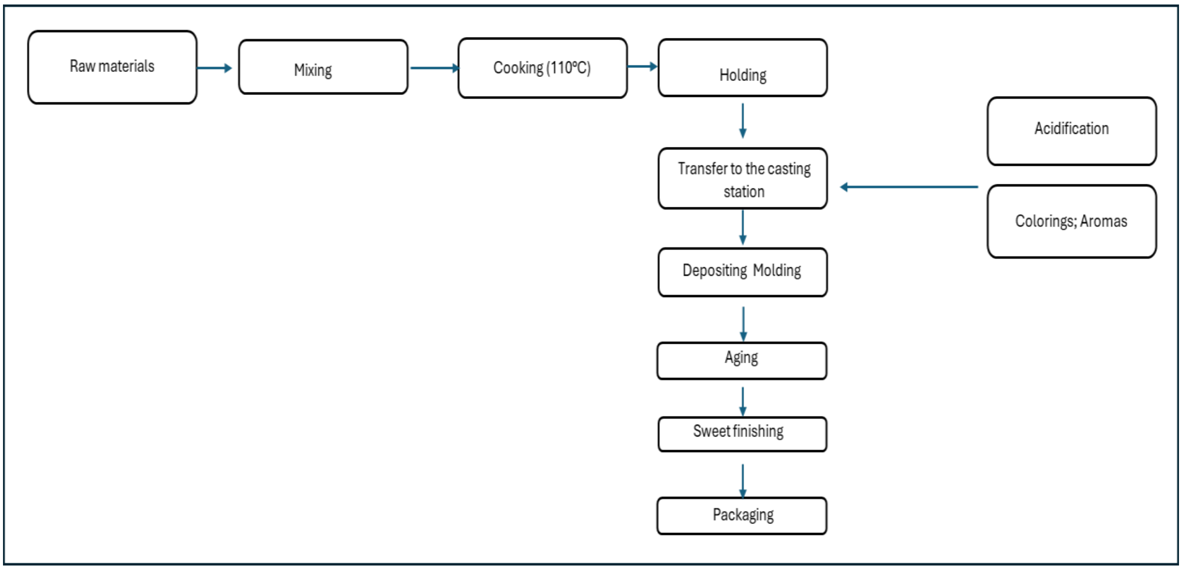

Figure 1: Gummy candies flowchart

3. Process Phases with IoT Sensor Implementation

To design a smart control system of process operations involved in gummy candy production, real-time data monitoring is required. Such a system consists of a network of IoT (Internet of Things) sensors that collect data during critical production stages. The rationale of sensors' network is described the following and summarized in Table 1.

Table 1: IoT Sensor Type Implementation

Process Phase	IoT Sensor Type	Monitored Parameter	Quality and Process Benefits
Ingredient Dosing	Weight sensors, automatic dosers	Solid and liquid ingredients controlled by digital recipes	Precise dosing, reduction of batch-to-batch variability, uniform texture and structure, waste reduction, traceability
Mixing	Inline viscometers Speed sensors	Mix viscosity Mixing speed	Uniform distribution, prevention of texture defects, improvement of homogeneity and final quality
Cooking & Holding Tank	Temperature sensors (Pt100) Optical refractometers Inline viscometers	Temperature % soluble solids (Brix) Viscosity	Gelation control, crystallization prevention, maintenance of optimal consistency
Acidification	Inline digital pH meters	pH, Acidity	Precise control of gelation, prevention of excessive acidity, optimal flavor balance
Flavouring & Colouring	Flow Sensors Optical Sensors / IoT Spectral Colorimeters	Amount of flavors and colorants Color uniformity	Sensory reproducibility, improvement of visual appeal, prevention of incorrect coloring or defects
Moulding	Optical sensors (high-speed cameras, 3D vision) Temperature and moisture sensors	Temperature and moisture Shape, size, defects, viscosity	Detection and elimination of defective products, correct filling of molds, uniform aesthetic and structural quality
Aging in Ovens	Temperature and relative humidity (RH%) sensors with PID controllers	Humidity, Temperature	Microbiological stability, shelf- life improvement, aging time optimization, energy efficiency

Ingredient Dosing: Weight sensors, together with the automatic dosing system, ensure the correct amount of each ingredient in every batch. Since each component has a specific role, even slight variations can affect the texture, taste, and appearance of the candies. A balanced formulation promotes a more efficient production process, minimizing defects and guaranteeing candies with optimal texture, flavor, and appearance. The gel system appears many strong bonds when the sugar content increases and the dry matter concentration increases, leading to increased binding on the gel network making the hard structure of gummy candy (Nguyen et al., 2024). The sugar-to-water balance is crucial, as it impacts the mixture's viscosity and mouthfeel. The presence of sugar co-solutes can increase the strength of gelatine gels up to a maximum co-solute concentration, beyond which the gel weakens due to a lack of water available to maintain the integrity of the gel (Tirek et al., 2023). Factors contributing to excessive water content may also include an improper sugar mixture (including a possible sucrose inversion phenomenon), ineffective cooking temperature, or too short a drying time (Gunes et al., 2022). Sucrose, combined with glucose syrups, improves the texture and sensory properties of gummy candies. In addition to acting as a sweetener and providing structure, sucrose helps reduce haze and enhance thermal stability. It is often used in concert with glucose syrup, as the syrup can enhance sucrose solubility and retard sucrose crystallization in food products. Use of higher viscosity glucose syrup (lower moisture or higher DE) will slow sucrose molecule migration and inhibit graining (Burey et al., 2023). Glucose syrups serve to contribute to the texture and sensory properties of the gels. They also offer several functional benefits, including reducing moisture absorption, optimizing the manufacturing process, and adjusting texture and sweetness. They also help preserve candies by lowering water activity, preventing microbial growth, and eliminating the need for preservatives (Tirek et al., 2023). Gelling agents influence the texture; incorrect dosing may result in a product that is too hard or too soft and sticky (Nguyen et al., 2004a). Typically, a higher content of hydrocolloids and a lower water content result in firmer candies. Differently, if the product is too soft, it may contain too much water, an insufficient concentration of hydrocolloids, or an incorrect choice of hydrocolloid (e.g., a gelatine Bloom value that is too low) (Nguyen et al., 2024b).

Mixing: Sensors monitor the mixing speed to ensure mixing is done at desired shear conditions. Particularly, inline viscosimeters tracks mix viscosity to ensure homogeneous distribution of ingredients.

Cooking and Holding Tank: Accurate temperature monitoring during syrup cooking is a critical step in gummy candy production, significantly affecting their texture, stability, and overall quality. At this stage, sugars, gelling agents, and other ingredients are dissolved and heated to specific temperatures to achieve the desired structure. Poorly managed thermal variations can compromise quality, leading to structural and sensory defects. Insufficient cooking temperatures may leave undissolved ingredients, resulting in a soft, unstable texture. Improper temperature control can also cause sugar crystallization, an undesirable phenomenon that alters the syrup's structure, making it rough and grainy while reducing elasticity and increasing brittleness. Additionally, excessive temperatures can trigger chemical reactions, degrading the gelling agents and affecting texture of candies. Overheating can also cause sugar caramelization, altering the colour and creating amber or brown hues rather than the desired bright colours. This can lead to bitter or toasted notes, negatively impacting the sweet, fruity profile of gummy candies. Furthermore, caramelization makes sugar less soluble, hardening the product and altering its chewability. Integrated sensors monitor the syrup’s temperature in real time during the gelling process to achieve the optimal gel matrix with most suitable mechanical and sensory properties. An indicator of the product's stability is the amount of total soluble solids which the final product should contain. Gummy candy should achieve at least 75 % total soluble solids to preclude mould growth (Delgado and Bañón, 2015). Refractometers integrated directly into production lines allow measuring the total soluble solids content in real-time, ensuring that the final product maintains the desired stability and quality. They measure the density of the product based on its refractive index, which changes depending on the concentration of dissolved solutes. In this way, they provide useful data for adjusting parameters such as temperature, mixing speed, or cooking time to ensure that the concentration of soluble solids remains within the desired limits. As for mixing, rheological sensors or inline viscosimeters tracks cooked mix viscosity to ensure uniform deposition in molds, avoiding defects like air bubbles or texture defects.

Acidification: Citric acid is the most used in gammy candies production. The ionic strength and pH have a strong effect on gel formation, so it is important to control pH and maintain appropriate acidity levels to ensure cohesion and stability. Acidity and pH influence the strength of gelatine gel; an excess of acid leading to low pH levels reduces gel strength due breaking gelatine bond. The result is a decreased product hardness (Gunes et al., 2022). A correct dosage, in addition to ensuring structural stability throughout production and storage, enhances the candy's flavour, balancing sweetness with a fresh, fruity notes. A well-calibrated dosage improves the sensory experience, while an excess can result in an overly sour and unpleasant taste, reducing consumer acceptance (Nguyen et al., 2024). In line pH-meters address the effect of acidity on gelling efficiency, enabling timely corrections to prevent non-compliant batches and ensuring food safety standard.

Flavouring and colouring: Strict control over flavours dosing ensures that each production batch maintains a consistent taste profile, ensuring long-term uniformity and meeting consumer expectations. Flavouring agents are added at the last moment of production, as they are volatile and can be degraded by high temperature. Flavourings must be dosed into the product accurately, at a precise temperature and blended well to ensure even flavour dispersion (Burey et al., 2023). It is important that the aroma is correctly selected and dosed according to the type of hydrocolloid used. The concentration of gelatine can affect the rheological properties and the textural characteristics of the candies, which may lead to differences in the release of flavour compounds, particularly due to interactions between the flavour molecules and the proteins (Gunes et al., 2022). The visual appeal of gummy candies depends also on accurate colorant dosing which must ensure vibrant and uniform tones without unwanted streaks or discoloration. Colour is indeed one of the most important quality indicators in confectionery products because makes the candies attractive to the consumer, influencing their purchase decision. In most cases, a concentrated solution of colorants is added after the cooking phase. The usage level of food colorants varies depending on their nature (artificial or natural) and the type of product. It also depends on factors such as pH, acidity, thickness of the piece, transparency, type of hydrocolloid, and method of finishing the piece (e.g., oiling, sugar sanding, etc.) (Gunes et al., 2022). Colour defects that can arise from non-conducive conditions include discolouration, fading, loss of sparkle, which can be affected by supply variations, inadequate mixing, and poor storage (Burey et al., 2023). In-line optical sensors allow for the early detection of these defects and the application of real-time corrections.

Moulding: IoT sensors in the syrup moulding phase enable real-time monitoring of key parameters such as temperature, moisture, and viscosity, which directly affect gel formation and solidification within the moulds (Efe and Dawson, 2022). Accurate temperature control ensures that the product is poured in optimal conditions, preventing gelatine from setting too quickly or too slowly, which could compromise texture and aesthetic quality. Inline optical sensors during the moulding phase constantly monitor that the candies have uniform sizes and shapes, preventing defects such as irregularities, air bubbles, and deformations. They ensure that the syrup is correctly distributed into the moulds, preventing the formation of hollow. Optical sensors also monitor the colour, ensuring that it remains in line with visual standards and that any unwanted changes can be quickly corrected.

Aging in Ovens: After moulding, gummy candies are cooled and aged in tunnels or chambers to achieve a consistent solid matrix. During this step water activity is reduced to an acceptable level to achieve microbiological stability. The texture changes from soft to hard as the strength of gel increase. The process conditions depend on the composition of the jelly, the size of the product, the viscosity of the deposited gel, and the temperature variation during production. Uncontrolled changes in moisture content can lead to quality defects such as premature crystallization, excessive stickiness or hardness, lack of structure, loss of chew, hardness, poor handling on machines, and product flaws in surface texture as crusting. All defects which may decrease consumer acceptability (Burey et al., 2023). Inside the climatic chambers, the use of sensors provides precise temperature and humidity monitoring, reducing the risk of defects in the final product and ensuring texture quality that meets production standards and consumer expectations. IoT sensors monitor humidity levels and automatically adjust temperature to maintain the ideal process conditions, ensuring proper aging and achieving the desired texture without affecting chewability. To optimize this phase, the process variables could be correlated with data derived from - texture profile analysis (TPA). TPA simulates the first two bites of the food mastication process, making the technique very suitable for studying the deformation of viscoelastic materials (Delgado and Bañón, 2015), such as gummy candies. Predictive models that include parameters such as hardness, gumminess, and chewiness allow for precise determination of the texture stabilization time, enabling the adjustment of temperature, humidity, and aging time, thereby reducing process time, energy consumption, and improving the stability and quality of the final product.
Data collected from inline sensors and final quality controls is used to train a machine learning model that detects patterns and anomalies by correlating operating conditions with product quality. During production, the system compares real-time data from IoT sensors with the pre-trained model. This approach enables the implementation of adaptive control, dynamically intervening to correct any deviations from optimal parameters. When the system detects significant deviations from target values, it can automatically adjust critical process variables, such as ingredient dosing, temperature and time of the heat treatment, to maintain ideal conditions. In cases where anomalies cannot be corrected autonomously, the system generates notifications for operators, allowing timely and targeted intervention. Thanks to the model's incremental learning capability, the system continuously refines its predictions by integrating data from new production batches. This adaptive approach not only improves the accuracy of predictive analyses but also drives the continuous improvement of the gummy candy production process, directly impacting waste reduction and optimizing the quality of the final product. The implementation of the system requires adequate technological infrastructure and specialized expertise (Ortiz et al., 2023). Once the system identifies deviations from optimal parameters, the production plant must be equipped with a PLC (Programmable Logic Controller) or other industrial automation systems capable of adjusting critical variables in real-time. Additionally, visualization software is essential for operators to monitor production status, view quality predictions for ongoing batches, and receive alerts of potential anomalies. An intuitive graphical interface facilitates data interpretation and enables quick human intervention when necessary. For data management and storage, the system must include an efficient and scalable database (Figure 2).

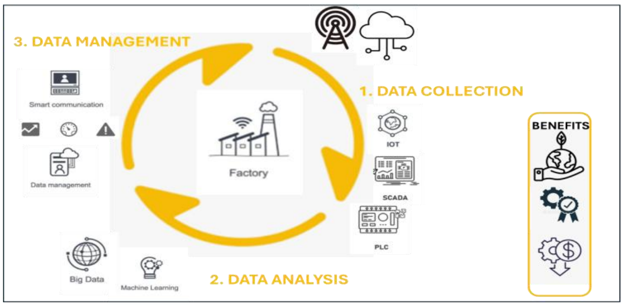

Figure 2: Industrial IoT Data Cycle

4. Conclusions

The proposed integrated approach, which combines IoT sensors, artificial intelligence, and quantitative methods, represents a significant innovation for the gummy candy industry. In addition to ensuring consistent and predictable product quality, the system offers numerous operational and strategic advantages. Real-time analysis of process parameters enables waste reduction, optimization of production phases, support for R&D activities, and a more efficient response to the demands of a dynamic and constantly evolving market. Another key benefit is the improved traceability of products throughout the entire production chain. Thanks to the structured collection and storage of data, it is possible to recover information accurately of each batch, monitoring operating conditions and any deviations from optimal parameters. This not only facilitates quality control and the management of non-conformities but also allows for a swift response to potential product recalls, ensuring greater consumer safety and compliance with regulatory standards. The adoption of this technology, therefore, not only fosters continuous improvement in the production process—enhancing overall efficiency and quality—but also contributes to a more transparent and reliable production management system, strengthening the company's competitiveness in the market.

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