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A comprehensive review of direct, indirect, and AI-based detection methods for milk powder

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This paper summarizes the existing methods of milk powder detection, and classifies them according to the direct and indirect characteristics of the detection methods, mainly introducing the detection methods of milk powder nutrition, recombination characteristics, transportation convenience and sensory characteristics. The direct detection methods of milk powder include traditional chemical analysis and modern instrument technology, most of which are based on the International Dairy Federation (IDF) standard method and powder detection instrument method. These methods can give accurate quantitative results, but often require complex sample preparation processes and long experimental operations. The indirect detection methods of milk powder mainly use microscopic imaging, spectral analysis, electronic nose system, environmental parameter monitoring and other technologies to establish complex mathematical models and provide a fast and non-destructive alternative. In addition, this paper summarizes the development of milk powder quality detection in three main directions: first, the traditional chemical detection method to environmental protection indirect analysis technology; Secondly, the development direction of multidisciplinary comprehensive evaluation; Finally, there is the wider use of artificial intelligence (AI) and automation. Future developments in the field are expected to focus on innovation across disciplines, combining technologies such as spectroscopy, high-definition microscopic imaging, digital twin with modern technologies such as AI and the Internet of Things. These advances are expected to improve the efficiency, sustainability and intelligence of milk powder quality assessment systems, while ensuring their accuracy and reliability.

KEYWORDS

milk powder, quality detection, artificial intelligence, rapid detection, spectrum, indirect detection

1 Introduction

Milk powder is a favorite source of nutrition for many consumers, and it lasts a long time. Therefore, its quality, safety and resilience directly affect the consumer experience. According to the World Health Organization, milk powder is an important source of protein and calcium worldwide (Pancholi et al., 2023), and is especially important for children and the elderly (Li et al., 2023; Nebbia et al., 2023). As more and more people drink milk powder, ensuring its nutritional value and ease of brewing has become a problem for the food industry to solve.

The main ingredients of milk powder include protein, fat and lactose. The quantity and proportion of these ingredients not only determine the nutritional value of the product, but also affect consumer acceptance and market competitiveness (Schaefer et al., 2023). In order to ensure the quality of milk powder, the industry usually uses a variety of methods to evaluate the physical and chemical properties, structural properties and sensory properties of milk powder (Wang et al., 2024). In this paper, the detection methods are divided into direct detection and indirect detection according to whether auxiliary indicators are used. The direct detection method is mainly formulated by ISO and other organizations, its advantage is high accuracy, the experimental process has standards to follow. However, this method also has the problems of complex operation, error prone and low efficiency. In contrast, indirect detection methods predict hard-to-measure parameters by measuring easily available indicators. The advantage of this method is that the detection speed is fast and the damage to the sample is small, but it also has the problem of low accuracy and relying on the quality of the direct detection data. In recent years, many efforts have been made to improve the accuracy of indirect detection methods. Khan et al. (2020a) summarized the application of hyperspectral imaging in real-time quality control of milk powder, and Sharma et al. (2021) modeled the hygroscopic isotherm in milk powder by using computational neural genetic algorithm. In actual production, sometimes the precise measurement of certain milk powder parameters is not as important as quickly determining whether the product meets regulatory requirements. In view of this situation, Liu et al. (2023b) developed a method combining near-infrared spectroscopy and algorithm for rapid detection of trace elements in infant formula milk powder, and Ding et al. (2023) realized the LSTM algorithm for rapid detection of energy content in infant formula milk powder.

In the following sections, this review will discuss in detail the direct and indirect methods for detection the physical and chemical parameters, remodeling properties, and sensory properties of milk powder. Particular attention will be paid to the role of AI technology in indirect detection methods. Finally, the future development trend of milk powder detection technology will be discussed.

2 Main focus of Milk powder quality detection

The quality detection of milk powder is mainly carried out based on the aspects of nutritional value, recombination difficulty, transportation efficiency, sensory experience and so on. This chapter discusses, in detail, the key indicators to be measured in milk powder quality detection.

2.1 Nutrient content

When checking the quality of milk powder, the content of protein, fat and lactose are the most critical chemical indicators, which directly affect the nutritional level and market performance of the product. According to ISO 23318:2022 (Poo et al., 2024), the protein content of whole milk powder accounts for 34% of skim milk solids, while the protein content of reconstituted milk powder should meet or exceed 16.7 g /100 g. Whole milk powder should have a fat content of 26 g/100 g or more, and lactic acid concentration of reconstituted milk powder should not exceed 18°T. According to ISO 20633:2015 (Vassos et al., 2024), infant formula has more stringent standards for protein, lactose, linoleic acid, vitamins, minerals, taurine and other ingredients than ordinary milk powder.

2.2 Ease of reconstitution

In addition to controlling the nutritional composition of milk powder, it is also important to precisely adjust its recombination characteristics, because this will affect the production efficiency and the stability of product quality. In addition, these characteristics will directly affect the feelings of consumers when using and the market competitiveness of the product. Wettability, dispersion, sinkability and solubility are the important criteria to evaluate the recombination characteristics of milk powder, and also the key factors to judge the quality of milk powder products (Ji et al., 2016b).

Wettability is defined as the diffusion and permeability of water molecules on the surface of milk powder particles when they come into contact with water molecules (Hailu et al., 2023), which directly affects the dissolution kinetics and dissolution uniformity of milk powder when dissolved, and is an important indicator in the preparation of milk powder (McSweeney et al., 2020). The wettability of milk powder is mainly affected by factors such as particle density, particle size distribution, porosity, specific surface area, surface charge characteristics, and interface properties (Fournaise et al., 2020). The study by Yasukuni et al. showed that particle size distribution and surface characteristics were the most important indicators affecting the wettability of milk powder.

Dispersibility is defined as the ability of milk powder aggregates to disperse into individual particles in water with gentle agitation (McCarthy et al., 2014). There is a strong correlation between milk powder dispersibility and wettability, and milk powders, which usually exhibit excellent dispersibility, also have excellent wettability. The dispersibility of milk powder is mainly affected by factors such as particle morphology, particle size distribution and surface characteristics. Crowley et al. (2015) showed that milk powders with particle sizes in the range of 150–250 μm had the best dispersion and performed better than 30% of those outside of this range. In another recent study, the effect of manufacturing parameters on the dispersion of milk powder was equally important (Schuck et al., 2016). Dispersibility is particularly important in infant formula, as it is used as an indicator for the preparation of milk powders, because infant formulas with excellent dispersibility will have higher nutrient utilization and digestibility.

Sinkability is an important functional property of milk powder, which means that milk powder particles can travel through the surface of the water when they hit it instead of floating on it (Anup Sharma et al., 2012). It is found that this characteristic has a great influence on the transformation effect, and is related to the wettability and dispersion. The main factor of sinkability is the relationship between particle density and surface tension. Dense particles sink better than lighter ones. In addition, the porosity of the particles also affects the subsidence. In the most suitable porosity range, the particles can both remain structurally intact and quickly immerse in water.

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Solubility is an important characteristic of milk powder, which refers to the ability of milk powder to form a uniform solution after being remixed in water (Wu et al., 2022). This property involves several aspects, such as wetting, dispersion and sedimentation. Although it is difficult to study these individual processes, solubility is still the best criterion for evaluating the reaction between powder and water (Schuck et al., 2012). Studies have shown that solubility has a great impact on production efficiency and economic benefits. Sikand et al. (2011) found that protein content and storage conditions would affect the solubility of powder. The more protein, the lower the solubility. This conclusion is similar to those observed by Gaiani et al. (2007), who also noted that the composition of the powder's surface has an important effect on its dispersibility in water. In addition, Crowley et al. pointed out that environmental factors, especially humidity and temperature during storage, would also significantly affect solubility.

2.3 Transport convenience

Flowability is an important feature of milk powder, which refers to the ease with which particles can move during packaging, storage and transportation. Physicochemical factors affecting fluidity include particle size distribution, cohesiveness between particles, amount of oil on the surface, average particle size and roughness of the surface. In particular, it should be noted that the particle size distribution is the key to determine the quality of fluidity; Powders with good fluidity usually contain more large particles and a small number of small particles. If the proportion of fine particles (≤100 μm) is too large, it will affect the flow and make the flow difficult. A higher proportion of larger particles (≥200 μm) helps to improve fluidity, as it reduces friction between large particles (Liu et al., 2023a). In addition, the content of water and fat can also affect mobility; Too much water makes the particles more likely to stick together and reduce fluidity, while a high fat content can form a lubricating film on the surface of the particles, helping to reduce friction and thus improve fluidity (Fitzpatrick et al., 2004).

Bulk density is an important criterion to evaluate the transportation economy and market display effect of milk powder, which directly affects the performance of milk powder in the process of production, storage, transportation and consumption. This is also an important factor in judging the quality of milk powder. Bulk density refers to the quality of milk powder per unit volume and is a key indicator used to measure the efficiency of packaging, storage and transportation. This property is affected by many factors, such as the size of the particles, the Spaces within the particles, and the arrangement of the particles in the container. In addition, determining bulk density is also very important for controlling transportation costs, because it will affect the economic benefits of long-distance transportation of milk powder (Ding et al., 2020b).

2.4 Sensory characteristics

Sensory characteristics such as color, fragrance and taste are very important for the overall evaluation of milk powder. Generally speaking, milk powder should be white or light yellow, mainly because of the fat content and heating process at the time of production (Czarnowska-Kujawska et al., 2024). For example, whole milk powder is usually yellowish in color, while skim milk powder is closer to white. In terms of smell, milk powder should have the taste of fresh milk, not sour or other strange taste, which usually indicates the preservation of the product and whether it is fresh (Guo et al., 2023). Taste is the most direct feeling of consumers; Good milk powder should taste delicate, sweet, should not have bitter, sour or metallic taste and other bad taste (Coolbear et al., 2022).

3 Direct methods for quality detection of Milk powder

In order to accurately measure the important characteristics of milk powder, international standards organizations such as IDF have developed quantitative measurement methods. These methods generally require the use of laboratory equipment to directly detection the milk powder. In this paper, direct detection refers to the use of laboratory instruments, by measuring the number of some specific indicators, to directly or indirectly determine the indicators to be detected. This chapter will explain these direct detection methods in detail.

3.1 Nutritional value assessment methods

There are several standard techniques for the direct detection of nutrients in milk powder. Fat content was determined mainly by Soxhlet extraction and modified Mojonnier method (Gallier et al., 2017). For protein determination, Kjeldahl nitrogen determination is still the most reliable method, but spectrophotometry can also be a faster option (Dupont et al., 2012). Lactose is usually determined by enzyme method and high performance liquid chromatography (HPLC) technology. The latest research shows that advanced HPLC-MS technology improves the accuracy of determination (Hou et al., 2019). Acidity is usually measured by electropotentiometry and titration, while the total solids content is determined by traditional oven drying and refraction techniques (Murphy et al., 2015). Table 1 lists the direct methods for detecting the nutritional value of milk powder.

3.2 Reconstitution performance assessment methods

3.2.1 Wettability

According to ISO/TS 17758:2014|IDF/RM 87:2014, methods for improving the dispersibility and wettability of instant milk powder are described. Common wettability detection methods include contact Angle measurement, settling time and capillary rise method. Figure 1 shows these methods in action.

Contact Angle measurement is to detect the contact Angle between the water drop and the surface of the milk powder by using an goniometer. The contact Angle can be used to roughly judge the wettability of milk powder. The smaller the contact Angle, the better the wettability of the milk powder (Ji et al., 2016a).

The IDF method is as follows: Put 10 grams of skim milk powder or 13 grams of whole milk powder into a 400 mL beaker, and then place the beaker in 25°C water. Next, the already weighed powder is poured into

TABLE 1 Direct detection methods for determining the nutritional composition.

Nutrition	Methods	Reference	Brief Description of Methods
Protein	Kjeldahl method for nitrogen determination	Jones (1991)	Calculation of protein content via nitrogen determination
	Lowry colorimetry	Junior et al. (2023)	Use phenol reagents to react with proteins to generate colored compounds for colorimetry
	Radial immunodiffusion assay	Niero et al. (2023)	The antigen (protein) solution is poured into the gel wells and as it diffuses radially, a precipitate circle is formed in the medium, the diameter of which is used for quantification
	Enzyme-linked immunosorbent assay	Sánchez et al. (2002)	Enzyme-labeled antibodies. ELISA tests based on antigen (protein) reactions
	Ultra-high-performance liquid chromatography-quadrupole time-of-flight mass spectrometry	Xi et al. (2017)	Separation using a C18 column and detection with a quadrupole time-of-flight mass spectrometry system
Fat	Alkaline hydrolysis method	Liang et al. (2021)	Extract the sample alkaline hydrolysate with anhydrous ether and petroleum alcohol, then distill to remove the solvent and weigh the residue
	Gerber method	Andrade et al. (2022)	Measure the volume of fat after separation
	Babcock method	Chen and Ellefson (2024)	The sample is acidified, causing the fat to rise to the top, and the fat volume is measured using a graduated cylinder
	Infrared spectroscopy	Ye et al. (2017)	Quantifies fat content by measuring the sample's absorption of infrared light
Lactose	Enzymatic method	Mangan et al. (2019)	Lactose is decomposed by lactase, and the resulting glucose and galactose can be determined via colorimetry or the electrode method
	Colorimetry	Portnoy and Barbano (2021)	Using the molybdenum blue reaction to quantify added glucose and galactose in milk
	High-performance liquid chromatography	Kučerová et al. (2017)	Separation and quantification of lactose using instrumentation
	Capillary zone electrophoresis	de Oliveira et al. (2021)	Under the action of the electric field, the lactose molecules in the sample move at different speeds in the capillary
	Nuclear magnetic resonance spectroscopy	Vasiljevic et al. (2021)	A one-dimensional H NMR spectrum was established using amine amide and citric acid as the quantitative external and internal standards, respectively
Minerals	Titration	Mandal et al. (2024)	Determination of calcium content via titration
	Ion chromatography	Wei et al. (2017)	For separation and quantification of minerals
	Wet digestion method	Hui et al. (2022)	The milk powder sample is mixed with acids (such as nitric acid or hydrochloric acid) and subjected to high-temperature digestion, converting minerals into soluble forms for further analysis
	X-ray fluorescence spectroscopy	Johnson and King (1987)	Uses X-rays to excite elements in the sample, analyzing emitted fluorescence to determine the mineral content
pH	pH meter method	Wu et al. (2019)	Use a pH meter to directly measure the pH value of reconstituted milk to determine its acidity
	Indicator method	Pugliese et al. (2017)	Add pH indicators to the solution and observe color changes to assess acidity or alkalinity
	Titration	Jaudzems et al. (2019)	Add standard acid or base dropwise to the solution until neutralization, calculating the volume used

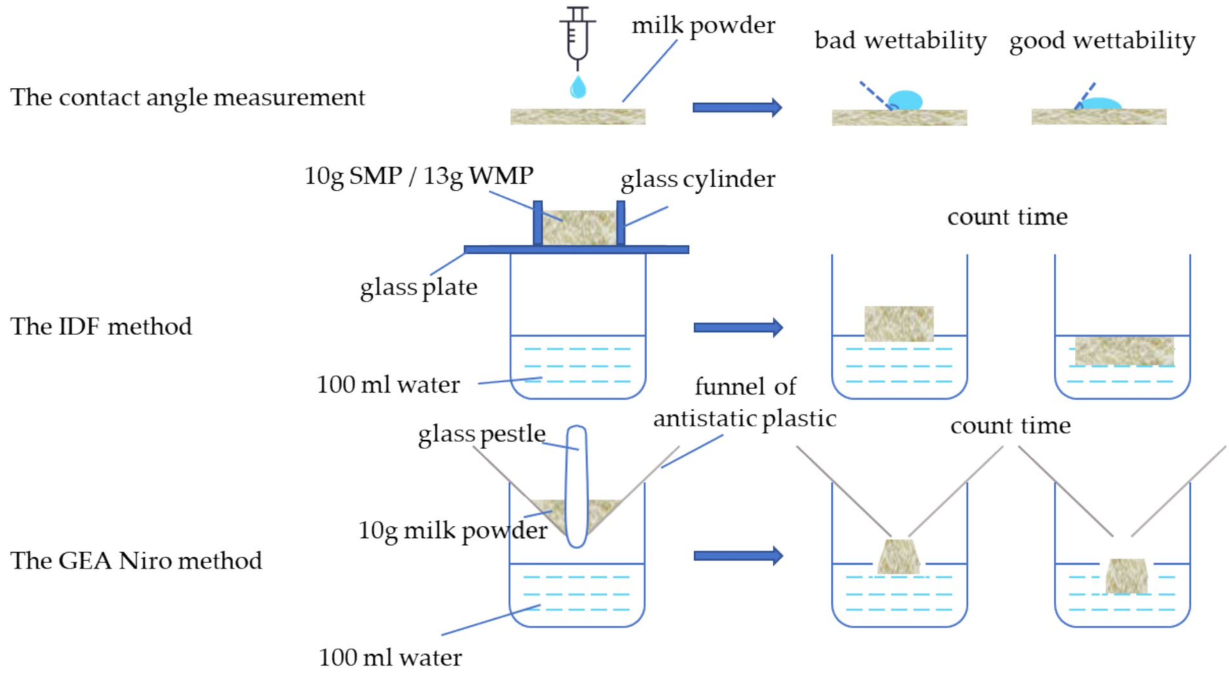

FIGURE 1
Illustration of direct detection methods for milk powder wettability.

a glass cylinder, which is placed on the glass plate above the beaker. After that, remove the glass plate and start the timer. Wettability, also known as wetting time, refers to the time it takes for the last particle in the powder to pass through the water surface (Warncke and Kulozik, 2020).

The Niro method uses a funnel made of antistatic plastic foil, placed on the side of a beaker, with a glass rod as a stopper, and a water temperature of more than 20°C. Sprinkle 10 grams of powder around the glass rod. When the glass rod is lifted, start timing with a stopwatch (van Boven et al., 2023).

3.2.2 Dispersibility

The main methods for directly detecting the dispersion of milk powder are dissolution method and New Zealand Dairy Board method (NZDB method).

Dissolution detection requires manual operation, and the steps are complicated. The method is to take the right amount of milk powder and water, mix at 25 degrees, stir continuously for 20 s, and then use a 150 micron sieve to filter out the solid particles that are not dispersed. The proportion of solids in the reconstituted milk is then calculated to determine the dispersion of the milk powder. The more solids in the liquid, the better the powder is dispersed.

The NZDB method (Písecký, 2012) simplifies laboratory operations and reduces overall time, but does not solve the real-time measurement problems of the international standard method. According to the NZDB method, 26 grams of milk powder is dissolved in 200 mL of distilled water at 20 degrees Celsius. Stir quickly with a fork to swirl the solution, then pour the mixture into a settling funnel and vacuum it through a 300-micron stainless steel sieve within 5 s. The undissolved milk powder is left on the sieve, dried and weighed, and the dispersion is expressed as a percentage of the undissolved substance.

3.2.3 Sinkability

The main direct detection methods for evaluating the subsidence characteristics of milk powder include subsidence detection, turbidity measurement and density measurement.

Sinkability detection is to dissolve a certain amount of milk powder in water, put it in the water for a period of time to see the situation of the sediment, and then measure the volume or weight of the sediment to judge the characteristics of the sediment.

The solubility of milk powder was measured by turbidimetry. A low turbidity may indicate a high concentration of suspended particles or sediment.

Specific gravity measurement evaluates the settlement by measuring the change in the specific gravity of milk powder in water. Higher specific gravity generally means better dispersion and less likelihood of settlement.

3.2.4 Permission to reuse and copyright

The main basis for evaluating the solubility of milk powder is ISO 8156:2005|IDF 129:2005. In addition to this standard, there are two methods: transparency assessment and turbidity measurement.

The insolubility index method is a basic method used to measure the solubility of milk powder (Lin et al., 2022). Because this method can be repeated and is closely related to actual production applications, it is widely used.

Transparency evaluation is to put the milk powder into water and observe the clarity of the water to determine whether the milk powder can dissolve well. A spectrophotometer measures how much light passes through; The more it penetrates, the better it dissolves.

Turbidity method is the use of turbidity meter to determine the turbidity of dissolved milk powder solution. The lower the turbidity, the better the dissolution effect. Turbidimeters provide stable and repeatable measurement results, making them suitable for quality control in mass production.

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3.3 Factors affecting transport convenience assessments

3.3.1 Flowability

The measuring methods of fluidity include Angle of rest method, discharge time method and drum method. The Angle of rest detection is to drop the milk powder from a certain height to the horizontal surface, and then measure the diameter of the cone formed, which is the Angle of rest. The smaller the Angle of repose, the better the fluidity. This method is simple to understand, but is easily affected by ambient humidity and temperature. The discharge time detection uses a Hall flow meter to measure the time required for a given amount of milk products to pass through a standard hole. The shorter the time, the better the liquidity.

3.3.2 Bulk density

In accordance with ASTM D7481-18 (Astm, 2018) method for measuring powder loose and vibrational bulk density in a cylinder, we use a powder characteristic tester to measure the loose bulk density of milk powder. First, a small spoon is used to add the milk powder sample through the feed port and pass the sample through a sieve into a special loose density measuring container. When the container is full and slightly overflows, stop filling. Next, use a triangular metal scraper to smooth the surface of the container. Finally, the total weight of the powder and container is recorded, and the loose packaging density is calculated using the corresponding formula.

According to ISO 8967:2005|IDF 134:2005 Standard method for measuring the vibration density of powder products, the vibration densitometer consists of a fixed 100 mL empty cup and an extension cylinder. Put the milk powder into this long container and close the lid. The device is then fixed in a specific position and subjected to 3,000 vibrations. After the vibration is over, use a triangular metal scraper to smooth the surface of the container. The total weight of the powder and container is then recorded, and the corresponding formula is used to calculate the vibration density.

3.4 Sensory characteristic assessment methods

Visual, olfactory, gustatory, tactile and auditory evaluation are the most basic and direct evaluation methods. The sensory evaluation of milk powder is mainly subjective. In order to quantify sensory properties, these methods can be listed in Table 2.

TABLE 2 Sensory evaluation methods.

Senses	Methods
Visual Assessment	Instrumental colorimetry
	Trained panel assessments
	Digital imaging analysis
Olfactory Assessment	Systematic scoring method using static headspace analysis
	Common Descriptors
Taste Assessment	Quantitative scoring system based on descriptive analysis
Tactile Assessment	Smoothness evaluation
	Tendency for agglomerate formation
Auditory Assessment	Assessment of the relationship between operational sound quality and freshness

4 Indirect methods for quality detection of milk powder

In this paper, indirect detection is defined as the measurement of the quality characteristics of milk powder in the laboratory, and then the establishment of links between these quality characteristics and other representative characteristics of the sample, so that only these optional sample characteristics can be used to quickly assess the quality characteristics. Figure 2 illustrates this process.

Due to the difficulty of establishing indirect detection correlations and the fact that most methods rely on AI, these methods may not fully cover all aspects of milk powder quality detection. Table 3 lists the main differences and advantages of existing direct and indirect detection methods. This section describes the methods in terms of each specific method, rather than categorizing them by the quality attribute being measured.

4.1 Image-based indirect detection

Microscopic imaging can provide detailed information about milk powder particles. The optical microscope works at a certain magnification and can simultaneously display the details and distribution of different particles (Murrieta-Pazos et al., 2012; Gaiani et al., 2011). As the magnification of the microscope increases, more surface details of milk powder particles can be seen, but some sense of proportion may be lost (Kim et al., 2002). The characteristics of these microscopic images are helpful for indirect quality detection of milk powder (Burgain et al., 2014; Fu et al., 2012). The morphological characteristics observed by microscope are closely related to the quality parameters of milk powder. Recent studies have shown that particle size distribution and surface micro-structure are related to some important quality properties, such as wettability, impermeability, and fluidity. Advanced image analysis techniques can now measure these appearance features, making it an effective tool for rapid and non-damaging sample quality inspection.

Ding et al. (2020a) introduced a method to predict the dispersion degree of milk powder through the image of milk powder particles, which was completed under a tenfold optical microscope. They took pictures of milk powder particles with an optical microscope and then processed these pictures with computer technology. After removing noise and converting them into black and white images, they extracted characteristics such as roundness, convence, solidity, maximum diameter, minimum diameter, area, equivalent diameter,

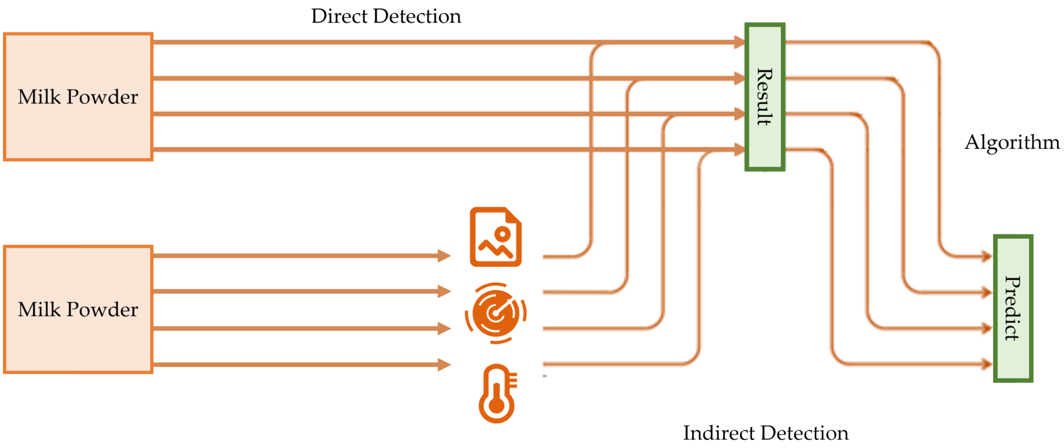

FIGURE 2
Logic diagram of direct and indirect detection.

circumference and elongation of milk powder particles. Then, they used principal component analysis (PCA) to study the effects of these characteristics on the dispersity of milk powder, and found that roundness, convexity and area were the main factors affecting the dispersity of milk powder. They then trained the model with partial least square method (PLS) and artificial neural network (ANN), and the results showed that the ANN-based model had better prediction results. In addition, Ding et al. also conducted another study using a similar method to predict the loose and packing density of milk powder by analyzing the image of milk powder particles under a tenfold optical microscope.

The latest study by Ding et al. (2024) proposed a simpler method, which is to put together pictures of milk powder particles taken under a 10x microscope, so that pictures containing the proportion and shape information of milk powder particles can be obtained. They trained a ResNet model using these images and the corresponding dispersion and volume density data as datasets. The trained model can directly predict the dispersion quality and packaging density of milk powder samples from the input pictures.

Harindran et al. (2022) used laser confocal scanning microscopy to observe the dry state of the recombinant emulsion under three conditions of dilution, solidification and storage, so as to predict the situation of milk powder. These pictures show what the reconstituted emulsion looks like at different stages of treatment, and the different states of the milk powder can be analyzed through these pictures. They chose a feedforward neural network (FFN) as the basic model for classification and trained it with representative picture data for the three states. The trained model was able to predict the type of composite emulsion with 85% accuracy and effectively determine whether the sample was diluted, solidified, or deteriorated.

Yan et al. (2020) developed a method for predicting the type of milk powder suspension using a lenless camera. They recorded the transmission speckle image of suspension under coherent He-Ne laser irradiation with a lenceless camera. These images show dispersion and transport patterns related to the concentration of the suspension. The convolutional neural network (CNN) was trained using these images as a dataset, and the trained model was more than 99% accurate on the test set.

4.2 Spectrum-based indirect detection

The spectroscopy can be used to detect milk powder quickly, and can obtain the composition and quality information of milk powder comprehensively. There are different kinds of this technology depending on the wavelength. Near infrared spectroscopy (NIRS) has a working range of 780–2,500 nm and can detect protein, moisture, and fat in milk powder with very few samples (Wu et al., 2008; Hebling et al., 2022). As the frequency increases, more detailed chemical information on milk powder can be obtained by spectroscopy, although the accuracy of this information may be affected by the signal-to-noise ratio (Gastélum-Barrios et al., 2020). The spectral technology can effectively complete the indirect quality detection of milk powder (Velásquez-Ferrín et al., 2021; Du, 2024). By analyzing the spectrogram, we can understand the quality parameters of milk powder, such as the change of milk powder protein, the crystallization of lactose and the stability of reconstructed milk powder through the specific spectral band and its intensity change. Combined with AI technology, this method can achieve rapid and accurate quantitative indirect quality detection of milk powder.

Huang W. et al. (2022) performed a rapid elemental analysis of milk powder using laser-induced breakdown spectroscopy (LIBS). They compared five AI techniques: convolutional neural networks (CNN), linear discriminant Analysis (LDA), K-nearest neighbor (KNN), random forest (RF), and support vector machine (SVM). The average accuracy rate of CNN in detecting the adulteration of different foreign protein milk powder reached 97.8%. This research has developed a simple, reliable and efficient method for the detection of milk powder adulteration.

Near infrared spectroscopy (NIR) is very helpful for quality assessment and adulteration detection of milk powder. Ejeahalaka and On (2020) studied a near infrared spectroscopy method for the detection of melamine and urea in fertilizer milk powder (FMP) containing vegetable oils such as coconut oil, palm oil, soybean oil, and sunflower oil. They used a partial least squares regression model that predicted a sum of squares (PRESS R2) of more than 95% when the amount of adulteration reached 1.00% or more. This method provides an affordable option for the testing of FMP products and

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TABLE 3 Differences and advantages between direct and indirect detection methods.

Application	Direct Method Features				Indirect Method Features			
	Method	Overview		Turnover Time	Method	Overview		Turnover Time
		Advantages	Disadvantages			Advantages	Disadvantages	
Nutrient content	Alkaline hydrolysis method; Kjeldahl method for nitrogen de-termination	High accuracy, unified use of standards;	Cumbersome process, high consumable cost, some professional threshold, easily affected by irrelevant factors	1–4 h	Prediction of difficult-to-measure indicators based on easy-to-measure milk powder indicators	No need to pre-treat samples, fast speed, non-destructive testing, suitable for large-scale testing	The instrument is relatively expensive and no unified standard has been formed	20–60 min
Reconstitution performance	NZDB-method; IDF 129:2005.	Simple and easy, low consumable cost	Prone to human errors, low efficiency and not convenient for large-scale detection	10–120 min	Image-based dispersion prediction	Rapid measurement, high accuracy, high efficiency, suitable for large-scale sample testing	Highly dependent on high-quality data, with certain errors	5–10 min (without training cost)
Transport convenience	IDF 134:2005 Repose angle testing	Simple method, unified standards, high accuracy	Large sample consumption and long-time consumption	20–60 min	Image-based bulk density prediction	High efficiency, low consumable cost, low loss	Certain errors, difficult to quantify	5–10 min (without training cost)
Sensory characteristics	Instrumental colorimetry	Unified standards, simple testing	Large subjective errors, low efficiency	1–3 h	E-nose-based detection	Qualitative measurement, more objective;	High equipment cost, complex operation	5–10 min (without training cost)

helps safeguard public health. Huang G. et al. (2022) developed a fast and simple method for detecting food adulteration through spectral analysis. Their approach is to extract simple features from complex spectral data with an autoencoder and reconstruct the original spectrum. By comparing the errors before and after coding to determine whether the food is adulterated. The effect of this model is consistent with the infrared spectral data of milk powder and its adulterated version. The experimental results show that this classification method is better than the existing method based on support vector machine, and can be flexibly used for spectral detection of food adulteration. Khan et al. (2021) and Khan et al. (2020b) used near infrared spectroscopy, data preprocessing and multivariate analysis to predict the fine particle size fraction, dispersion and packing density of different milk powder samples. They achieved a high prediction accuracy of 88–90% using a partial least squares (PLS) regression model. This provides a new way to detect the characteristics of milk powder, which can be effectively applied in large-scale quality control in factories.

MALDI-TOF mass spectrometry can detect protein in milk very sensitively and is very effective in detecting adulteration of milk powder. Rysova et al. (2022) used this method to detect adulteration in small ruminant milk and developed calibration models for goat and sheep milk. They used PLS regression and Lasso regularized generalized linear models to analyze the concentration of adulterated milk in small ruminant milk. Zhang et al. (2022) developed a method combining MALDI-TOF mass spectrometry and AI for the analysis of the composition and quality of milk and dairy products. They selected the characteristic peptide mass spectrometry signals by PLS-DA, LASSO, and RFECV. The prediction accuracy of SVM-L, RF, LDA and PDA are 0.97, 0.96, 0.96 and 0.96 respectively, which can accurately identify heat treated milk samples.

Nuclear magnetic resonance (NMR) spectroscopy and chromatography-mass spectrometry have become effective tools for the identification and characterization of milk. Rysova et al. (2021) used NMR spectroscopy and multivariate analysis (PCA and OPLS-DA) in the spectral range of 0.04 ppm to find specific biomarkers that could distinguish cow's and goat's milk. They found that nacetylated carbohydrates are unique to cow's milk, and that nacetylglucosamine and nacetylgalactosamine can be used to check whether cow's milk has been mixed with cow's milk. Studies have shown a strong positive correlation between the amount of nacetyl carbohydrates and the proportion of milk. The ROC curve was used to verify the model. The results showed that the detection accuracy of 5% adulterated milk could reach 84.78%, and the detection accuracy of 10% adulterated goat milk could reach 95.65%. Sanchez et al. (2021) conducted a comprehensive study to develop a method combined with nuclear magnetic resonance (NMR) and gas chromatography–mass spectrometry (GC–MS) for characterizing the liquid and volatile components of New Zealand GMP (sugar macropeptide). Their non-targeted 1H-NMR analysis identified 44 metabolites from the fat, sugar, and aromatic regions of the liquid portion. In addition, their nontargeted HS-SPME-GC–MS method isolated 50 volatile compounds from different chemical families. These volatiles include 26 aliphatic hydrocarbons (mainly alkanes), 8 ketones, 4 alcohols, 3 aromatics, 3 olefins, 2 aldehydes, 2 esters, 1 acid and 1 sulfur compound. This study demonstrates the power of NMR based metabolomics in characterizing the water-soluble components of GMP.

4.3 Environmental parameter-based indirect detection

Production environment monitoring provides important information for the quality of milk powder. In the production of milk powder, the process control system operated by multiple sensors can simultaneously collect real-time environmental parameters and production line conditions (Vieira et al., 2019; Munir et al., 2015). Although the extended monitoring scope may affect some operational flexibility, we can obtain more comprehensive information about the production batch environment (Wang et al., 2018). These environmental monitoring data can be used for preliminary quality checks of milk powder (O'Callaghan and Cunningham, 2005; Uthayaseelan, 2024). The environmental parameters obtained by continuous monitoring are closely related to the quality characteristics of milk powder. The latest study found that temperature changes, humidity and air flow patterns in particular reflect important quality characteristics of milk powder, such as moisture content, particle aggregation and microbial stability. Advanced data analysis methods can predict quality parameters based on environmental conditions, making it a useful tool for proactive quality control and batch consistency assessment.

Boiarkina et al. (2017) devised a test to assess how poorly powdered milk is absorbed during production. This method is easy to operate and solves some problems of the previous detection methods. It is only necessary to collect some data on the production line and information about the size of milk powder particles, and you can roughly judge the dispersion of milk powder. However, this test can only roughly classify dispersion into high, medium and low levels, and cannot perform specific numerical analysis. This method provides a fast and effective inspection method for factories.

Wagh and Agashe (2023) used machine learning and data analysis techniques to design an analytical system to monitor changes in product density in a four-effect falling film evaporator for milk. This system handles different process parameters collected by the evaporator, such as temperature, pressure, and flow. After feature extraction and data preprocessing, a density prediction model is established, which can realize real-time monitoring and optimization of production process. This research focuses on the development of models to predict product density by using data collected from multiple sensors and machine learning methods to improve the quality of production and products.

4.4 E-nose-based indirect detection

Electronic nose technology provides characteristic information about the volatile characteristics of milk powder. Gas sensor arrays work with multiple sensing elements to simultaneously capture overall aroma patterns and specific volatile compound signals during milk powder analysis (Yu et al., 2008; Yakubu et al., 2022). With the increase in optional specialized sensor categories, the detection methods for specific volatile compounds in milk powder have also correspondingly increased (Darvishi et al., 2024). The signals generated by these electronic noses can be effectively applied to the indirect detection tasks of milk powder, as the volatile profiles produced by the electronic noses have a strong correlation with various quality parameters in milk powder (Mu et al., 2020). The odor characteristics and specific volatile markers in milk powder can reflect the oxidative state, storage stability, and quality attributes related to thermal damage. The use of electronic nose technology combined with AI pattern recognition enables non-destructive testing of milk powder.

Tian et al. (2023) combined electronic nose technology with gas chromatography to propose a rapid detection method for milk adulteration from multiple perspectives. The process of this method includes sample preparation, data preprocessing, feature extraction and selection, model construction and model validation. In the data preprocessing phase, we use techniques such as normalization and noise reduction to ensure data stability and quality. In the stage of feature selection and extraction, we use statistical and machine learning methods to select important features from the preprocessed d`ata and build a predictive model. In the model building stage, we chose Lasso regression, decision tree and random forest to train the training set, so as to build the prediction model. Finally, in the model validation stage, we verify the trained model on the test set through cross-validation, mean square error, determination coefficient and other evaluation indicators. Experimental results show that this analytical framework can effectively predict milk adulteration.

Chi et al. (2021) focus on the research of process control in food processing using electronic noses. They proposed a method for monitoring product quality in food processing that utilizes electronic noses as sensors, based on data analysis and machine learning. This method trains machine learning predictive models using processed electronic nose data, effectively monitors the food production process, optimizes production workflows, and ensures product consistency to achieve cost reduction and efficiency improvement.

Shuba et al. (2024) proposed an innovative sensor system and data processing framework to improve the monitoring efficiency of multiple variables in complex environments. By integrating e-nose data with machine learning algorithms, the system can accurately identify changes in key variables, providing real-time monitoring and prediction capabilities. The experimental results show that the system is significantly superior to the traditional methods in terms of the detection accuracy and response speed and effectively improves the operational efficiency and safety in industrial applications.

4.5 Water activity-based indirect detection

Water activity monitoring is the key index of milk powder quality analysis and shelflife prediction. Advanced sensor systems are integrated with the production line to continuously measure water activity and other processing parameters during milk powder production (Olaimat et al., 2020). As the measurement accuracy improves, a more detailed profile of the water activity in production batches can be obtained, although some operational complexity may increase (Juarez-Enriquez et al., 2022). These continuous monitoring data provide valuable insights for the rapid quality assessment of milk powder. Water activity measurements obtained through real-time monitoring showed that there was a strong correlation between various quality attributes of milk powder. Recent studies have shown that water activity patterns, especially during storage and processing, are highly indicative of key quality characteristics, such as powder stability, microbial safety and reconfiguration characteristics.

Wei et al. (2020) conducted a comprehensive study on the influence of water activity on the mechanics of Salmonella heatkilling activity in milk powder. Their study found a relationship between water activity and bacterial heat resistance, suggesting that the heat resistance of salmonella increased as water activity decreased. The study also pointed out that the different fat content of whole milk powder and skim milk powder had no significant effect on the heat resistance of Salmonella. The researchers created a model to connect the water activity in milk powder to the inactivation of salmonella, which could help the food industry predict the reference D value of salmonella under certain temperature conditions, that is, the time it takes to achieve bactericidal effect.

Yan et al. (2022) studied the relationship among water activity, lactose crystallization (LC) and the Maillard reaction (MR) in the simulated milk powder system. Their research showed that increasing the water activity (from 0.11 to 0.69) accelerated LC and MR processes across all model systems. Whey protein-lactose (WP-Lac) model showed the greatest change, the glass transition temperature decreased rapidly, and the structural change was also obvious. This is because whey protein has a simple structure and small molecular weight, which can also explain the phenomenon of high lysine consumption. As water activity increases, lactose forms a tighter crystal structure, and in the WP-Lac model, anhydrous beta-lactose crystals exhibit greater proteinbinding capacity and more water release, resulting in accelerated glycosylation and Browning. In contrast, casein-based models show fewer molecular changes and reduced lactose crystallization, while in casein-whey protein-lactogen models, interactions between proteins inhibit the production of glycosylation products.

5 Application of AI in milk powder quality detection

The technology of milk powder quality detection has changed a lot, from the traditional detection method to the modern analysis method (Ma et al., 2024c). In particular, with the rapid development of AI, its new application in milk powder quality detection is bringing new models for quality assurance (Ma et al., 2024a). Figure 3 shows the application of AI in milk powder detection. This chapter mainly introduces the latest research and future possibilities of AI technology in this field.

5.1 Application of regression models

Regression analysis is a statistical method used to determine the quantitative relationship between variables. The main idea is to build a predictive model through data fitting. Although the traditional ordinary least squares (OLS) regression method is widely used, it is not effective in dealing with multicollinearity problems. Partial least squares (PLS) (Stocchero et al., 2021) regression addresses this challenge by extracting the underlying factors from the original variables and performing dimensionality reduction in the predictor variables and response space. This kind of application has been widely used in some fields, such as chemometrics. Support vector machine (SVM) regression takes a completely different perspective, rooted in the structural risk minimization principles of statistical learning theory. By introducing kernel functions to map low-dimensional features to high-dimensional spaces, SVM effectively deals with

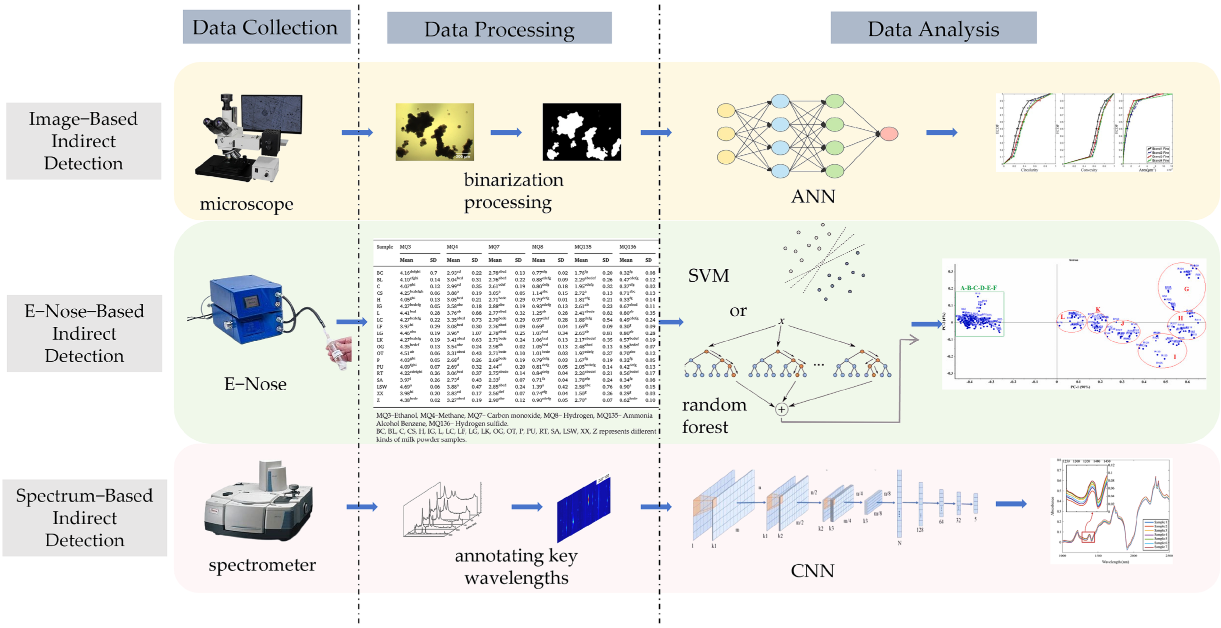

FIGURE 3
Methods of applying artificial intelligence technology in milk powder detection.

nonlinear regression problems. Kernel-based regression models, such as kernel ridge regression (KRR) (H. Zhang et al., 2023), solve nonlinear problems by identifying linear relationships in high-dimensional feature spaces. Each approach has its advantages: PLS is good at managing multi-collinear data, SVM is robust to outliers and exhibits strong generalization capabilities and KRR offers computational efficiency advantages.

At present, the quantitative methods used in milk powder quality detection mainly involve regression models, such as PLS and SVM. For example, Ding et al. used PCA and PLS for the rapid, indirect quantification of the dispersibility and bulk density of milk powder. Ejeahalaka et al. used PLS to detect whether the fat in milk pulp was adulterated. Similarly, PLS was also used by Khan et al. to analyze the fine particle size fraction, dispersion and packing density of milk powder. In addition, Tian et al. used linear regression, decision tree and random forest methods to quickly detect whether milk powder was adulterated. These regression models can predict difficult quality parameters from easily measured data, which greatly improves the efficiency of indirect detection of milk powder quality.

5.2 Application of computer vision

Computer vision technology is a deep learning method specifically used to process image data. Its basic principle is to analyze image features by imitating the layers of the visual system. The design of convolutional neural networks (CNNS) was influenced by the work of biologists Hubel and Wiesel (Hubel and Wiesel, 1962), who investigated the layers of information processing in the cat visual cortex. This layered design allows the deeper layers of the network to capture features that are relevant to a larger range of input images. In a neural network, this means that deeper nodes can see a larger range. This attention-based network model mimics the way the human brain processes visual information. The human brain scans roughly the entire field of vision and then quickly focuses on a specific area (Luo et al., 2016). This helps people quickly filter out unimportant information and focus on the key parts. Compared to other methods, the attention mechanism can extend the scope of observation better, cover the entire image, and pay more attention to the important parts (Itti et al., 1998).

Computer vision technology is widely used in milk powder quality detection (Ma et al., 2024b). For example, Ding et al. used ResNet model (A deep convolutional neural network architecture utilizing residual blocks with skip connections to mitigate vanishing gradients, enabling training of extremely deep networks and achieving breakthroughs in image recognition tasks) to predict the dispersion and packaging density of milk powder. Yan et al. trained the CNN model by transmitting the speckle model to distinguish different types of suspended matter. Huang et al. used the CNN model trained by laser induced breakdown spectra to analyze the element composition in milk powder. Compared with regression model, computer vision technology makes data analysis easier and can further improve the efficiency of milk powder quality detection. However, the application of computer vision technology in this field is still relatively small, and many advanced algorithms have not been developed. Because the image data related to milk powder is very diverse, the computer vision technology has great application prospects in the future.

5.3 Prospects for the application of recommendation systems and large language models

The rapid development of AI technology provides new opportunities for the quality inspection of milk powder. A large language model (LLM) built on the Transformer architecture

(Vaswani, 2017) (a neural network model using self-attention mechanisms to process sequential data in parallel, with stacked encoder-decoder layers and positional encodings for context awareness) can analyze the historical test data, expertise and scientific literature to develop high quality early warning systems. These systems leverage multi-modal data integration, combining sensory assessments, physicochemical parameters and expert insights to provide more comprehensive quality assessment recommendations. The recommendation system technology rooted in collaborative filtering algorithms can operate on the configuration of test parameters (Koren et al., 2009). By analyzing the detection history of different product batches, these systems can automatically recommend the most effective and reliable detection regimen for a particular type of milk powder, thereby increasing the efficiency of detection and the reliability of results. Graph neural networks (GNNs) (Veličković, 2023) implement supply chain traceability systems by building diagrams that connect raw materials, production processes and test phases. This helps monitor quality from start to finish and ensures a transparent and reliable quality control system. The combination of advanced technologies such as LLM for intelligent analysis, recommendation system for process optimization and GNN for supply chain monitoring will promote the progress of milk powder quality detection to a more intelligent and accurate direction, and provide stronger technical support for the safety of dairy products and consumers' trust.

6 Outlook on milk powder quality detection methods

In recent years, the quality detection technology of milk powder has improved greatly, both direct analysis and indirect detection, which use the technology of the time. With the continuous progress of science and technology, some new technologies have not been applied to the detection of milk powder, but the existing methods are also continuing to improve, which makes people full of expectations for future quality detection. Traditional detection methods are still the basis, while the application of new technologies makes the quality assessment of milk powder more accurate and efficient (Sokoliuk et al., 2022). At present, the combination of traditional methods and new technologies provides a new way of quality inspection, which requires us to seriously think about the future development path. This chapter will discuss the potential and possible application of new technologies in milk powder quality detection, focusing on new methods and technological innovation (Bowler et al., 2020).

6.1 Traceability and automation

Intelligent automation is the key development direction of milk powder quality detection in the future. The integration of big data analysis and automated systems will improve the efficiency, safety and reliability of milk powder quality inspection. Future automated systems will go beyond a single test phase to cover the entire quality inspection workflow. From automated sampling on the production line to automated analysis processes to automated data processing and feedback mechanisms, these systems will significantly improve test efficiency and accuracy (Jiang et al., 2022). For example, the combination of a robotic sampling arm and high-throughput detection equipment can significantly improve the detection flux and accuracy of milk powder analysis (Weston et al., 2021).

Internet of Things (IoT) technology will make milk powder quality monitoring smarter and more transparent throughout the supply chain. Smart sensors embedded in milk powder packaging can monitor key parameters, such as temperature and humidity, in real time during production, storage and transportation, ensuring quality compliance at every stage (Younan et al., 2020). The implementation of blockchain technology can further ensure the security and immutability of data, achieve full traceability from production to consumption and enhance consumer confidence in milk powder products (Rejeb et al., 2020).

6.2 Interdisciplinary integration

The future development of milk powder quality detection will not only depend on the progress of a single discipline but also depend on the integration and integration of multiple technical fields. The integration of knowledge of chemistry, physics, biology and information technology will make a more comprehensive, accurate and efficient milk powder quality detection method possible (Farag et al., 2022). Interdisciplinary cooperation is becoming a key trend in milk powder quality control. For example, near infrared spectroscopy combined with immune sensors can detect trace contaminants, such as antibiotic residues and aflatoxins, in milk powder with high accuracy (Liang et al., 2020). Microfluidic technology from physics, when integrated with biosensors, enables a fast and accurate analysis with minimal sample consumption, making it particularly suitable for the point-of-demand detection of milk powder quality and safety events (Farag et al., 2021). In addition, new nanomaterials play a crucial role in milk powder quality detection (Ma et al., 2024b). For example, graphene-based biosensors can detect ultra-low concentrations of harmful substances in milk powder, including heavy metal ions and organic pollutants (Seth and Rathinasabapathi, 2022). This combination of technologies enables the optimization of the entire process, enabling efficient management of every link from production to quality control to logistics on a single platform. An important example of interdisciplinary collaboration is the use of cold plasma technology in milk processing. This method is different from traditional chemical and heat treatment methods, and shows good bactericidal effect on whole, semi-skimmed and skimmed milk, while not significantly changing important indicators such as color and pH value. Although plasma sterilization technology is becoming increasingly popular, the application in milk purification, especially using low-temperature plasmas, demonstrates new areas of plasma physics and dairy science. This suggests that an interdisciplinary approach has the potential to transform the traditional way dairy products are processed (Ucar et al., 2021). Cooperation between different disciplines is increasing. Future research will not only advance in a single field, but also foster collaboration among experts in chemistry, physics, and data science (Amiri et al., 2021). Through indepth multidisciplinary integration, more intelligent and comprehensive detection methods can be developed to improve the quality detection level of milk powder.

6.3 Environmental protection and sustainability

In the traditional milk powder quality detection, the traditional chemical methods often rely heavily on toxic chemical reagents and consumables. Not only do these methods pose potential health risks and negative environmental impacts for operators, but there are also resource inefficiencies and waste generation issues (Alizadeh et al., 2021). For example, Kjeldahl nitrogen determination for protein content uses large amounts of sulfuric acid and selenium compounds as catalysts, which release toxic fumes during heating (Hueso et al., 2022). Soxhlet extraction relies on organic solvents (such as ether or chloromethane) to determine fat content (Masotti et al., 2020) and involves volatile and flammable substances that pose environmental hazards and need to be properly disposed of after analysis (Câmara et al., 2022). In addition, these solvent-based extraction methods typically require longer extraction times and high energy consumption (Mao et al., 2024).

However, people are increasingly concerned about environmental protection and sustainable development, and many modern detection techniques are slowly replacing traditional methods. For example, non-destructive techniques such as spectroscopic analysis (NIR, FTIR) can quickly determine the composition without the use of chemical reagents (Ziyaina et al., 2020). Biosensors can be used for specific detection with little waste generation (Girigoswami et al., 2021). New technologies such as ultrasound-assisted extraction and supercritical fluid extraction offer a more environmentally friendly option for composition analysis (Nde and Foncha, 2020). Microfluidic devices enable accurate analysis while significantly reducing reagent usage (Neethirajan et al., 2011). Advanced membrane separation technology provides an efficient and environmentally friendly sample handling method (Du et al., 2022). These emerging technologies, along with assistive tools such as AI algorithms, IoT monitoring and blockchain traceability, are pushing milk powder quality inspection in a more sustainable direction. These environmental technologies not only improve the safety of testing, reduce environ-mental pollution, but also improve the efficiency of resource use, in line with the global sustainable development goals.

6.4 Prospects of more future technologies

Looking to the future, the integration of new technologies provides new opportunities for milk powder quality detection. The development of quantum sensing technology can significantly improve the accuracy of inspection, and advanced nanomaterials and smart sensors can allow real-time online monitoring systems to better integrate into intelligent production processes. In addition, advances in edge computing and 5G/6G technology will make it possible to establish a distributed test network, enabling instant data sharing and analysis across the global supply chain, and ensuring consistent quality standards worldwide. In addition, the use of synthetic biology and biosensing platforms can provide highly specific and sensitive detection methods for trace substances and contaminants, while advances in microfluidic technology may lead to lab-on-a-chip solutions that require a small number of samples to complete a full quality assessment. These technologies will further promote the popularization of the application of non-destructive full inspection, leaving no potential problems on each milk powder production line unnoticed.

7 Conclusion

This paper summarizes the key indicators of milk powder quality detection, the existing direct detection methods and the emerging indirect methods. It discusses in detail the application of AI in indirect detection. Milk powder quality is evaluated on four dimensions: nutritional content, reconstitution, ease of transport and organoleptic properties. Direct detection methods, including traditional chemical analysis and modern instrumentation techniques, provide precise measurements but require complex sample preparation and lengthy processing. In contrast, indirect methods such as microscopy, spectroscopic analysis, and electronic nose techniques can enable rapid, non-destructive detection, but often require complex calibration models. The integration of AI enables indirect detection with greater accuracy and efficiency while eliminating human-induced bias, effectively bridging the performance gap between direct and indirect methods.

According to current research, the quality detection of milk powder has been developed in three main aspects. First, in terms of intelligence and automation, with the progress of AI technology, it will be more applied to milk powder detection, and with the development of intelligent detection technology, more open data sets will be provided. More advanced algorithms will make quality assessment faster and more accurate. New technologies such as the Internet of Things and blockchain will further improve the quality inspection system, ensure the implementation of inspection responsibilities, and promote the evaluation of test results. Secondly, in the field of interdisciplinary fusion, the future indirect detection methods will utilize more advanced equipment for extracting the physical and chemical characteristics of milk powder and obtain richer spectral information through improved imaging equipment and advanced spectral technology, so as to obtain enhanced image features. Future feature extraction will go beyond current imaging and spectroscopy methods, as developments in materials science, acoustics and other technologies will bring a whole new perspective to milk powder detection. Finally, in terms of green and sustainable development, although some traditional methods have become the standard process for testing relevant parameters, because these methods rely on toxic chemicals and consume a lot of resources, people are looking for more green and sustainable alternatives.

Author contributions

XS: Funding acquisition, Supervision, Writing – original draft. SS: Writing – original draft, Writing – review & editing. GD: Formal analysis, Writing – review & editing. HD: Funding acquisition, Writing – original draft, Writing – review & editing. ZX: Writing – review & editing. LW: Investigation, Writing – original draft. WC: Formal analysis, Writing – review & editing.

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Conflict of interest

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Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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