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Foreign Object Detection and Characterisation in Natural Rubber: A Review of Challenges, Techniques and Industrial Practices

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The characteristics of natural rubber, that is its elasticity, resilience, and cost-effectiveness, are the main reasons for its extensive usage in systems for vibration, noise, and structural shielding. Nonetheless, the existence of impurities, including metals, polymers, minerals, and fibres, might bring the natural rubber products' reliability, safety, and performance to a halt. Such contaminants usually get into the rubber during the buying process, cutting to size, and processing. Their severity varies, making their detection quite difficult, as these impurities differ in size, type, and form. Various approaches are currently used to locate and identify these materials. Among the techniques applied are mechanical sieving, magnetic and eddy current separation, optical imaging, and X-ray and computed tomography scanning. Besides that, surface and chemical analysis methods like inverse gas chromatography and Fourier-transform infrared spectroscopy are also part of the process. This research explores the effect of foreign contamination on the natural rubber's mechanical, dielectric, and environmental properties and further points out the major drawbacks of the current inspection techniques employed in the industry. The three main future research directions are: the use of artificial intelligence, non-destructive electromagnetic and microwave sensing, and the development of uniform benchmarking frameworks for real-time industrial quality monitoring.

Keywords: natural rubber (NR); foreign object contamination; non-destructive testing (NDT); dielectric characterisation; microwave sensing; quality control; isolation materials.

I. INTRODUCTION

Natural rubber (NR) is a raw material of great significance all over the world and is an indispensable input for many industries such as automotive, aerospace, medical, construction and consumer goods (Marrero Nunes *et al.*, 2025). The natural rubber output of Malaysia in 2022 was approximately 377,000 metric tons, which made the country the seventh-largest producer in the world. However, it was a far cry from Thailand and Indonesia, which were the first two in the world and produced around 4.82 million and 3.13 million metric tons, respectively (Review, 2023). A very stringent quality grading system known as Standard Malaysian Rubber (SMR) has been established by Malaysia to regulate the quality of their rubber. The SMR system was based on the grading of rubber using parameters such as ash content, dirt, nitrogen, plasticity, and viscosity and has been regulated by the Malaysian Rubber Board since 1965. The SMR grades CV50, CV60, and SMR 20 are among those that have been internationally recognised for their consistency, traceability, and performance standards (Jaswan Singh, Yusof & Mohd Rasdi, 2023). The methodological approach has been very helpful for Malaysia to promote its natural

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rubber products as top-notch and reliable ones in the world markets. The emphasis on sustainability has created an image of reused NR materials not only as cheap but also as eco-friendly substitutes for virgin rubber in various engineering applications, such as vibration isolation, acoustic damping, and structural cushioning (Dobrotă, Dimulescu & Stăncioiu, 2024; Na & Lee, 2024; Tejani, 2024). Their natural viscoelasticity and toughness make them suitable for use in the transportation, civil engineering, and industrial construction sectors.

However, maintaining product reliability remains a major challenge because foreign contaminants may be introduced during harvesting, processing, transportation, or downstream handling. Even small quantities of impurities can degrade mechanical properties, dielectric performance, and long-term material reliability (Dunuwila, Rodrigo & Goto, 2018; Sitepu, Matondang & Sembiring, 2019; Alam *et al.*, 2024; Inphonlek *et al.*, 2024). Conventional separation techniques such as sieving and magnetic removal remain widely used; however, recent advances increasingly employ sensing-based approaches including optical and near-infrared (NIR) imaging, X-ray computed tomography (CT), acoustic sensing, and spectroscopic methods such as FTIR and Raman analysis (Mohd Khairi *et al.*, 2018; Xie *et al.*, 2019; Bharadwaj *et al.*, 2021; Tang, Zhang & Mujumdar, 2022; Abdollahi-Mamoudan, Ibarra-Castanedo & Maldague, 2025). Despite these developments, significant challenges remain in achieving inline scalability, real-time detection, and standardised impurity classification (Yan *et al.*, 2020). A review, therefore, decides to critically analyse the technologies used for NR contaminant detection, their applicability in the industry, and the integration of AI-based inspection systems for quality control efficiency improvements through the review of AI-based inspection systems.

II. SOURCES AND TYPES OF FOREIGN OBJECT CONTAMINATION

Natural rubber (NR) foreign object contamination occurs during various steps of the rubber life cycle, from the collection of raw materials to mechanical processing and post-production handling. The contaminants, which include metals, minerals, synthetic polymers, and organic debris, can significantly affect the product performance, especially in applications where the purity of the material is crucial such as vibration isolation and dielectric insulation.

The contaminants in natural rubber are usually divided into three main source pathways: primary, secondary, and tertiary (Dvorak, Hnatkova & Sedlacik, 2016). Primary contaminants are the ones that come from the very first stages of natural rubber collection and coagulation (Ng, Othman & Yusof, 2022). In this regard, bark fragments, soil, residual moisture, and biological materials like leaves and fibres that may get caught in latex or sheet rubber can be included. What is more, chemical residues from coagulants (acetic or formic acid) or dispersants may cause changes in the surface chemistry of rubber, which in turn, may affect interfacial behaviour in composite formulations (Chang, Lyly & Sum, 2023).

Secondary contaminants are introduced during mechanical processing is mainly associated with the cutting, grinding, and recycling of end-of-life rubber products, especially tires. Introduced contaminants of this type may consist of metal fragments (both ferrous and non-ferrous) such as steel wires and aluminium flakes, textile reinforcements like polyester and nylon, and rubber–metal composite debris. Their hardness and density make these historical contaminants highly abrasive and capable of diminishing the mechanical and electrical insulation properties of the final product. Tertiary contaminants are those that appear after the main processing stages, typically during storage, packaging, or transportation (Sharma, 2024). Contaminants of this type may consist of plastic film fragments, airborne fibres, insect debris, and material cross-contamination from shared processing lines (Nene *et al.*, 2025). Although these impurities are often lower in concentration, they are morphologically diverse and can be hard to detect because of their small size, irregular shapes, and low contrast with the rubber matrices (Hanun, Hassan & Jiang, 2021; Zhang *et al.*, 2025).

In upstream operations, contaminants like soil and bark may get mixed during latex collection or result from improper cleaning of field equipment (Licht & Isebrands, 2005). Tire rubbers are very much prone to having steel rods, silica-based fillers, and synthetic cords inside. During the processing stage, tools from grinders or cryo-milling wear out and produce metal flakes, and the chemical residues from the use of lubricants and anti-adhesion agents are also part of the non-volatile contaminants. Moreover, dust from the environment, things from the package and transfer through the use of multi-material production equipment are among the post-processing contaminants that are frequently encountered. These contaminants vary a lot in size (from sub-micron particles to fragments of several centimetres in size), morphology (fibrous, granular, or flake-like), and chemical composition. A good number of them may be partially inside the rubber granules or be covered with processing films that make them very difficult to detect by traditional screening methods (Somwong, Wounchoum & Chongcheawchamnan, 2017). Magnetic separation and visual inspection methods may successfully eliminate larger metallic fragments, but they tend to miss smaller, non-metallic, and embedded particles. Hence, a complete detection strategy should integrate mechanical, optical, and spectroscopic technologies, with each of them adjusting to different contaminant's physical and chemical properties. Major types of foreign contaminants that are found in NR, their sources, material classification, and risk implications are summarised in Table 1 (Subramaniam, 1999; Venkatachalam *et al.*, 2013; Aye Khin *et al.*, 2020; Azizan *et al.*, 2021).

Table 1. Classification of foreign object contaminants in natural rubber

Type of Contaminant	Common Examples	Material Class	Source Pathway	Risk Level
Metallic	Steel wires, aluminium flakes	Ferrous / non-ferrous metals	Secondary	High
Mineral/Inert Solids	Stones, glass fragments, silica	Inorganic solids	Primary/ Secondary	High
Polymeric	PET, PVC, polyurethane, nylon	Synthetic thermoplastics	Tertiary	Medium-High
Fibrous Debris	Cotton threads, polyester, rayon fibres	Organic/synthetic fibres	Secondary/ tertiary	Medium
Organic Residues	Bark, wood chips, plant matter	Biogenic materials	Primary	Low
Chemical Residues	Grease, lubricant oils, plasticisers	Semi-volatile compounds	Secondary	Medium

III. METHODOLOGY

This research employed a non-experimental and qualitative method concentrating on non-destructive testing (NDT) and technology-based sensors for the detection and characterisation of foreign particles in natural rubber. The methodology was justified by the systematic literature review (SLR) where the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Mishra & Mishra, 2023), was the guiding principle, thus, prioritising studies that thoroughly discussed detection principles, sensor performance, and industry applications (Moher *et al.*, 2009). Besides, microwave patch antennas, dielectric measurements, X-ray imaging, scanning electron microscopy (SEM), and the likes of sensing methods in prioritising studies that have been done for the improvement of the quality and safety of natural rubber products were given special attention. For providing a complete technological and methodological analysis both the qualitative and quantitative research works were reviewed.

A. Search Protocol

The selection of articles and the collection of data were done through a systematic search that included the four major academic databases: IEEE Xplore, Scopus, Web of Science, and ScienceDirect. Moreover, Google Scholar was used for further research to include grey literature, and backward citation tracking. The period of publications for the search was set from January 2010 to June 2025 to be sure that the latest technological developments in NDT for the rubber industry were included. The search strategy employed keywords like "natural rubber", "rubber ", "latex", "foreign object", "contaminant", "inclusion", "microwave", "dielectric", "sensor", "X-ray", "non-destructive testing", and "scanning electron microscopy". In order to limit the results, Boolean operators (AND, OR) were employed, thus guaranteeing that the studies obtained dealt with both the material (natural rubber) and the method of detection.

B. Inclusion Criteria

Following were the criteria for inclusion: (I) studies published during the period from 2010 to 2025 in order to acquire recent advancements; (II) texts in English for better access to peer-reviewed international literature; (III) original research articles, conference proceedings, or theses from peer-reviewed sources; (IV) studies that were directly related to the detection or characterisation of foreign objects in natural rubber or similar polymeric matrices; (V) research that was carried out using NDT or sensor-based methods and provided detailed experimentation that made the methodological evaluation possible.

C. Exclusion Criteria

The studies listed below were not included in this review: (i) any articles that had been published prior to the year 2010; (ii) reports written in languages other than English; (iii) patents, technical notes, and news articles that have not undergone peer-review process; (iv) investigations that were entirely centred on synthetic rubber and had no indication of or reference to natural rubber; (v) destruction testing techniques that were not accompanied by a non- destructive or sensing technique; (vi) articles that were reviews and did not include primary experimental data.

D. Data Extraction

Data extraction was conducted using a structured protocol to ensure consistency and minimise bias. Two independent reviewers screened and assessed all selected studies, recording bibliographic information (author, year, title, source, DOI), study objectives, sample type, experimental setup, sensor specifications, detection principles, and key performance metrics. Any discrepancies were resolved through discussion until consensus was reached. Special attention was given to parameters such as detection accuracy, sensitivity, speed, and feasibility for industrial implementation. The final dataset comprised of eight studies meets all inclusion criteria, which are summarised.

IV. RESULTS

The first step of searching in the databases resulted in a total of 405 records which were obtained from seven different academic databases and sources: Scopus (n = 120), Web of Science (n = 85), IEEE Xplore (n = 48), ScienceDirect (n = 42), SpringerLink (n = 25), Google Scholar (n = 50), and conference proceedings (n = 35). Prior to screening, 115 records were eliminated, consisting of 95 duplicates, 15 records that did not match, and 5 records excluded for other reasons. Therefore, the title and abstract screening was conducted on 290 records. At this point, 200 records were eliminated as not relevant, e.g., no natural rubber or foreign object detection focus. The 90 records that survived that stage were then submitted for retrieval, and 8 of them could not be accessed. The other 82 records that had been retrieved were then evaluated for eligibility.

After the eligibility assessment, 74 reports were discarded on the grounds of the following reasons: not concerning natural rubber or contamination detection (n = 40), methods not suitable for NDT (non-destructive testing) application (n = 20), and lack of data for analysis (n = 14). In the end, 8 studies were granted with full compliance with the inclusion criteria and thus became a part of the final review. The study selection process was conducted rigorously following PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Figure 1 illustrates the flow of records through each stage, from identification to inclusion, while Table 2 presents the key characteristics of the studies included.

Dielectric property evolution during microwave-assisted devulcanization of ground tire rubber was monitored using an open-ended coaxial probe coupled with a vector network analyser (Pérez-Campos *et al.*, 2022). The system enabled continuous tracking of permittivity variations and demonstrated potential applicability for real-time monitoring of rubber processing conditions. Yu *et al.* (2025) investigated planar array antenna systems designed for operation in high-loss environments. The study demonstrated enhanced penetration capability and detection performance in dense and heterogeneous materials, with potential applicability to bulk rubber bale inspection. Nohlert *et al.* (2020) performed the same task using cylindrical microwave cavity resonators for detecting inclusions in granular materials. The system demonstrated sensitivity to small inclusions in the sub-millimetre range and was applied to flowing material conditions. Zeni *et al.* (2023) developed a differential microwave imaging approach aimed at reducing calibration complexity while enabling stable detection performance in inline processing conditions. Meanwhile, Marín-Genescà *et al.* (2020) provided dielectric characterisation data for polymer composites containing ground tire rubber, supporting material property modelling and system calibration for microwave-based sensing applications. (Ricci, Crocco & Vipiana, 2022) applied machine learning classifiers to microwave imaging systems, reporting improved classification performance for contaminant identification tasks based on feature learning from sensor data. Gueddida *et al.* (2022) demonstrated cylindrical resonator-based systems capable of stable permittivity measurement under moving material conditions, supporting continuous monitoring in flow-based systems. (Blasch, Liu & Zheng, 2022) reviewed multi-modal sensor fusion frameworks using deep learning approaches, highlighting their application across different sensing modalities for improved detection performance in heterogeneous datasets.

A comparative synthesis of the included studies indicates clear differences in performance among microwave and multi-modal sensing technologies in terms of sensitivity, detection limit, cost, and industrial readiness. Conventional microwave techniques such as open-ended coaxial probes and dielectric spectroscopy demonstrate high sensitivity to permittivity changes but are primarily limited to laboratory-scale or low-throughput environments due to slow measurement speed and restricted scalability. In contrast, planar array antenna systems and differential microwave imaging provide improved spatial coverage and better suitability for inline inspection, although they involve higher system complexity and cost. Cylindrical resonator-based approaches offer stable and reliable detection in flowing materials with moderate sensitivity to sub-millimetre inclusions, making them suitable for pre-processing stages, but their adaptability to heterogeneous industrial feedstocks remains limited. Recent studies further show that machine learning-enhanced microwave imaging significantly improves classification accuracy and reduces false detection rates, while multi-modal sensor fusion systems achieve the highest overall reliability by integrating complementary sensing principles. However, these advanced systems also introduce increased computational demand, cost, and complex integration. Overall, the comparative evidence highlights a trade-off between detection sensitivity, operational scalability, and industrial feasibility, reinforcing the need for hybrid and multi-modal inspection strategies in natural rubber quality assurance.

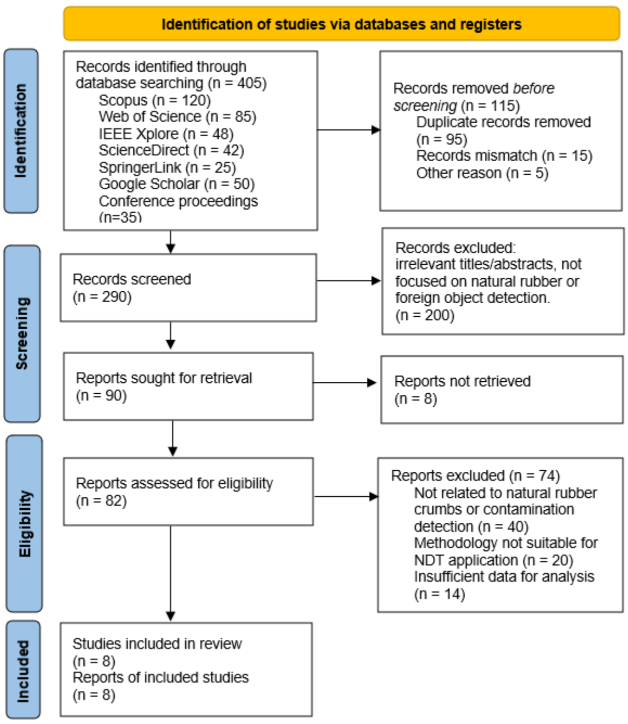

Figure 1. PRISMA flowchart

Table 2. Characteristics of the study included in this review

References	Technology Used	Material tested	Main findings	Relevance for Natural Rubber Inspection
(Pérez-Campos *et al.*, 2022)	Open-ended coaxial probe with VNA	GTR particles from recycled tires.	Detected dielectric property changes during GTR devulcanisation.	Can monitor real-time chemical changes during rubber processing, potential integration for process quality control.
(Yu *et al.*, 2025)	Planar array antenna system	Food emulsion with embedded metal and plastic contaminants.	High detection accuracy in high-loss media; deeper penetration.	Suitable for scanning thick rubber bales and detecting buried metallic/plastic contaminants.
(Nohlert *et al.*, 2020)	Cylindrical microwave cavity resonator	Sand with embedded metallic and dielectric objects.	Detected small inclusions in granular flows.	Applicable to inline crumb rubber inspection before bale pressing.
(Zeni *et al.*, 2023)	Differential microwave imaging	Packaged food with concealed contaminants.	Reduced calibration complexity; robust inline detection.	Allows rapid conveyor-based rubber bale inspection with minimal downtime.
(Marín-Genescà *et al.*, 2020)	Dielectric spectroscopy	LLDPE with varying % of GTR particles.	GTR content increased permittivity and loss factor.	Provides baseline data for tuning microwave detection on rubber with varying composition.
(Ricci *et al.*, 2022)	Microwave imaging with Machine learning classifier	Food samples with metallic/plastic contaminants.	Improved classification accuracy with AI-enhanced signal processing	Enables automated contaminant detection in rubber processing lines.
(Gueddida *et al.*, 2022)	Cylindrical resonator design under flow	Bulk granular and liquid materials.	Stable permittivity measurement in moving materials.	Can be adapted for continuous monitoring in rubber-crumb transport systems.
Blasch *et al.*, 2022)	Multi-modal sensor fusion with Deep learning	Multi-modal datasets from various industries.	Hybrid fusion outperformed single-sensor systems.	Supports future integration of microwaves with X-ray or optical systems for enhanced detection reliability.

V. CHALLENGES IN DETECTING FOREIGN OBJECT MATERIALS IN NR

The reliable detection of foreign materials in natural rubber (NR) remains challenging due to the diversity of contaminant size, morphology, density, and surface characteristics, as well as the limitations of currently available inspection techniques (Fořt *et al.*, 2022).

One of the major challenges is the similarity of physical properties between contaminants and NR particles. Lightweight polymers such as PET and polyethylene may exhibit similar colour, reflectance, or density profiles, making separation through conventional optical or density-based methods difficult (Guajardo & Andler, 2024). Fibrous contaminants may also become entangled within rubber crumbs and evade mechanical screening or airflow classification. In addition, contaminants can be partially or completely concealed by processing residues (Laftah & Wan Abdul Rahman, 2025). Metal inclusions, although detectable using magnetic or eddy current methods, may become oxidised, coated with rubber dust, or exist in non-ferrous forms, resulting in weak sensor responses (Yongzhen, 2024). Likewise, inorganic particulates such as silica or polymer films may become deeply embedded, reducing signal strength in infrared or X-ray-based systems (Abdollahi-Mamoudan, Ibarra-Castanedo & Maldague, 2025).

Detection efficacy is also influenced by contaminant position and geometry. Flattened flakes, threads, and irregularly shaped fragments may not be recognised accurately by imaging or spectrometry systems because of orientation effects and weak optical contrast (Karmali & Valilai, 2025). High-resolution techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and X-ray computed tomography (CT) provide improved material differentiation; however, their slow throughput, operational complexity, and high cost limit their suitability for inline applications (Ural, 2021; Ali, Zhang & Santos, 2023; Kassem *et al.*, 2023). In contrast, industrially compatible methods such as magnetic separation, ultrasonic scanning, and optical sensing offer improved scalability but often exhibit reduced sensitivity toward trace-level or non-metallic contaminants (Vasagar *et al.*, 2024).

Industrial environments introduce additional challenges including dust accumulation, vibration, moisture variation, and electromagnetic interference. Systems relying on stable optical conditions, clean surfaces, or low-noise environments are particularly vulnerable to performance degradation under factory conditions (Chis *et al.*, 2025). Furthermore, the absence of standardised detection methodologies and decision-making criteria complicates quality control implementation.

Overall, these challenges indicate that conventional single-mode detection approaches are insufficient for reliable contaminant identification in NR processing. Recent studies increasingly indicate a transition toward integrated and intelligent inspection frameworks combining magnetic, acoustic, optical, and chemical sensing modalities. These multi-modal systems, together with AI-assisted classification and real-time data analysis, have the potential to improve detection robustness and enable context-specific decision-making under complex industrial conditions.

VI. DETECTION AND CHARACTERIZATION TECHNIQUES

Natural rubber (NR) accurate detection and reliable characterising foreign substances involve a multidisciplinary approach due to the wide range of physical characteristics and chemical properties of possible contaminants. Detection methods should accommodate various particle sizes, shapes, types of materials, and circumstances of embedment, a lot of which cannot be properly handled by conventional single-mode inspection systems. Hence, a mix of mechanical, electromagnetic, optical, and spectroscopic methods is utilised, with each one presenting its own pros and cons in the industrial detection field.

A. Mechanical Sieving

Mechanical sieving is still the basic and most efficient method for the separation of oversized or heavy particles, especially those that are over the nominal size distribution of NR. Sieving is commonly used to get rid of coarse solids like stones, metal shavings, or large bundles of fibres. On the other hand, it is a method that cannot detect or separate fine powders, embedded impurities, or particles that have the same geometry as the rubber matrix. Generally, meshes with hole sizes between 2 mm and 5 mm are used to filter out large waste like metal pieces or stones. The screening efficiency (η) can be quantitatively expressed in terms of operational and design variables, such as mesh aperture size (a), screen length (L), vibration amplitude (Am), frequency (ω), and inclination angle (θ) (Aulton, 2017). To evaluate the performance of the mechanical sieving process in NR foreign-object inspection, three established screening measures were adopted and adapted from particle separation literature which are Percent Retained & Cumulative Percent Passing, Screening Efficiency for Vibrating Screens, and Overall Screen Efficiency via Oversize & Undersize Streams. Although effective for coarse contaminants, sieving cannot detect fine inclusions such as sub-millimetre particles or materials that pass through the mesh. It serves primarily as a pre-sorting or bulk cleaning step before more advanced analyses.

B. Magnetic and Eddy Current Separation

Magnetic separation is widely used to extract ferrous contaminants using drum magnets or magnetic belts, exploiting differences in magnetic susceptibility. Eddy current separators are used for non-ferrous metals including aluminium. Repulsive forces are induced by the eddy currents generated, and the particles are ejected from the bulk stream as a result of this repulsion (Oberteuffer, 1974). These methods work very well to eliminate electrically conductive contaminants; however, it fails the filtration of non-metallic or composite residues. The use of eddy current sensors makes it possible to detect non-ferrous metals, such as pieces of aluminium and brass, by observing the electromagnetic field changes caused by the presence of conductive materials. It face difficulties with thin, irregular or low-conductivity objects and are highly affected by background noise from nearby conductive infrastructure (Machado, 2024).

C. Optical and Spectral Imaging

Optical and near-infrared (NIR) imaging systems leverage camera-based detection and spectral reflectance to identify foreign matter based on colour, shape, or spectral signature (Mukhtar, Arbabi & Viegas, 2025). When machine learning classification algorithms are applied together, they provide the opportunity for inline monitoring of polymeric or visually recognisable contaminants at a high speed. Their presence in the Natural Rubber (NR) processing industry is still very limited, but it is developing, and thus, it requires specific spectral libraries and calibration. The combination of these systems with machine vision and artificial intelligence (AI) algorithms is becoming more common. NIR spectroscopy has an especially high-performance level in separating contaminating polymers like PET, PP, and PVC which have different vibrational absorption bands. Even though optical systems have the advantage of speed and integration in the process, they still have challenges such as being affected by the surface contamination, changing lighting conditions, and not being able to detect embedded or transparent particles. Furthermore, AI-based classifiers are data-demanding and might not perform as expected in the case of new or degraded contaminants (Islam, Fazle & Prodhan, 2022).

D. X-ray and Computed Tomography (CT)

X-ray radiography and computed tomography (CT) offer non-destructive internal imaging capabilities for detecting embedded or visually inaccessible foreign objects within natural rubber (NR). Advanced modalities such as dual-energy X-ray systems or photon-counting detectors enable material differentiation based on atomic density and attenuation coefficients (Pfeiffer, Pfeiffer & Rummeny, 2020). High-resolution micro-CT (voxel sizes of 10 µm) provides detailed morphological insight, making it highly suitable for research and forensic-quality control applications. However, these techniques typically require extensive scanning times ranging from several minutes to hours per sample and involve significant capital investment, shielding infrastructure, and operational expertise (Zabler *et al.*, 2021). As a result, their adoption in high-throughput industrial settings remains limited, primarily relegated to batch testing or confirmatory inspections.

E. Acoustic and Ultrasonic Methods

Acoustic detection probes density discontinuities within compacted NR blocks. Ultrasonic pulse-echo or acoustic emission techniques can identify embedded stiff or dense inclusions (Juan *et al.*, 2021). While non-invasive and promising for post-press quality control, these methods still require calibration and validation for specific crumb densities and geometries (Zheng *et al.*, 2021). These techniques are gaining attention for their non-destructive and inline scanning capabilities. However, their resolution is limited by acoustic impedance, and signal interpretation is often complicated by material heterogeneity and moisture content (Ensminger & Bond, 2023).

F. Advanced Surface and Chemical Analysis

Inverse Gas Chromatography (IGC) is employed in research settings to evaluate surface energy and polarity changes due to chemical contamination (Meyer *et al.*, 2023). This technique provides insight into the physicochemical interactions between rubber and fillers or surface residues, which can affect downstream bonding and performance. Nonetheless, inter-laboratory variability remains a challenge without standardised protocols. IGC yields both dispersive and specific (acid–base) surface energy components, useful for detecting polymeric or chemical residue on crumb particles. Besides, Fourier-Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy are used to identify chemical bonds and functional groups in surface layers, allowing precise identification of organic or polymeric contaminants (Xu *et al.*, 2019). These spectroscopic methods offer high specificity and are valuable for confirmatory analysis but are less suited to high-throughput environments due to long scanning times and sample preparation requirements (Fakayode *et al.*, 2020).

G. *Synthesis and Comparative Analysis*

The detection and characterisation of foreign objects in natural rubber (NR) remain challenging due to the wide variability in contaminant size, morphology, chemical composition, and embedding conditions. A review of the available techniques indicates that no single detection approach can address all contaminant scenarios effectively. Instead, each method exhibits distinct strengths and limitations depending on operational requirements and contaminant characteristics. Table 3 summarises the main detection methods discussed in Sections E-F.

Across the reviewed studies, comparative evaluation of detection technologies reveals systematic differences in performance metrics, particularly in terms of sensitivity, detection limit, operational cost, and industrial readiness. Mechanical and electromagnetic methods consistently demonstrate high industrial maturity and low operational cost; however, their detection capability is largely restricted to coarse or conductive contaminants typically above the sub-millimetre scale. Optical and near-infrared (NIR) imaging systems provide improved sensitivity for surface-level defects, achieving detection in the micrometre range, but their performance is strongly affected by environmental conditions such as lighting variation, dust accumulation, and surface contamination. Advanced imaging techniques such as X-ray and computed tomography (CT) achieve the highest spatial resolution, enabling sub-10 µm detection capability and internal visualisation of complex structures; however, their high cost, long acquisition time, and infrastructure requirements significantly limit industrial scalability. Acoustic and ultrasonic methods offer intermediate sensitivity and potential inline applicability but remain constrained by material heterogeneity, signal attenuation, and acoustic impedance variations within natural rubber matrices.

A noticeable trend across recent studies is the transition from conventional single-sensor approaches toward intelligent and data-driven inspection systems. Optical and NIR imaging combined with machine learning algorithms have increasingly been explored for real-time classification and automated decision-making. These approaches improve detection capability for visually distinguishable contaminants such as polymers and coloured residues. However, their robustness remains sensitive to environmental variability, requiring frequent calibration in industrial environments.

In parallel, microwave-based sensing and dielectric measurement techniques continue to develop as promising tools for material characterisation and contaminant detection. These methods offer penetration capability and sensitivity to dielectric property variations, making them suitable for embedded contaminant detection in bulk materials. Nevertheless, their performance is influenced by material heterogeneity and requires careful calibration across different rubber compositions.

Another emerging direction identified across the literature is the development of multi-modal detection frameworks. Instead of relying on a single sensing principle, recent studies increasingly integrate complementary techniques such as optical imaging, ultrasonic sensing, electromagnetic detection, and artificial intelligence-based data fusion. Comparative findings suggest that such integrated systems improve detection robustness and reduce false detection rates because different modalities compensate for the limitations of individual sensors. AI-assisted classification further enhances system adaptability by enabling feature learning and decision-level fusion across heterogeneous data sources.

From an industrial perspective, the adoption of foreign object detection systems must balance sensitivity, throughput, operational cost, and system complexity. While high-resolution laboratory systems such as CT provide excellent accuracy, their practical deployment in continuous processing lines remains limited. In contrast, scalable systems such as optical sorting, microwave sensing, and electromagnetic separation are more suitable for industrial environments but require further improvement in robustness and adaptability under real operating conditions.

In summary, industrial practice is gradually shifting from isolated detection technologies toward integrated intelligent inspection architectures. Future research should focus on developing scalable multi-modal frameworks, standardised benchmarking datasets, and real-time AI-driven sensor fusion systems capable of operating under variable industrial conditions. Such developments are essential to bridge the gap between laboratory-scale performance and full-scale industrial deployment in natural rubber processing.

Table 3. Summary of detection and characterisation techniques for NR contaminants

Technique	Detection Method	Sensitivity/ Resolution	Minimum Detectable Size	Cost	Scalability	Industrial Readiness (TRL)
Mechanical Sieving	Physical exclusion by size	Low (coarse separation)	>0.5mm	Low	High (inline pre-sorting)	TRL 9 (Fully mature)
Magnetic Separation	Magnetic susceptibility	Medium	~100 µm (ferrous)	Low	High (inline)	TRL 9 (Fully mature)
Eddy Current Separation	Electromagnetic induction	Medium (conductivity based)	~200 µm (non-ferrous metals)	Low–Medium	Inline, high throughput	TRL 8–9 (Industrial mature)
Optical / NIR Imaging	Spectral reflectance + AI classification	Medium–High	~50 µm (surface/near-surface)	Medium	High-speed inline sorting	TRL 7–8 (Emerging industrial)
X-ray / CT Imaging	Density contrast and volumetric internal imaging	High (tens of µm for X-ray; <10 µm for CT)	<10 µm	High	Batch-level only	TRL 4–6 (Limited industrial use)
Acoustic/ Ultrasonic	Detection of internal density discontinuities	Medium	~50–100 µm	Medium	Batch / limited inline	TRL 5–7 (Pilot stage)
IGC	Surface energy and chemical interaction analysis	Very High (surface energy sensitivity <1 mJ/m²)	Trace-level anomalies	High	R&D-level contaminant profiling	TRL 3–4 (Research stage)
FTIR/Raman Spectroscopy	Molecular vibrational chemical identification	Very High (chemical fingerprinting at µg scale)	~1–5 µm (trace films)	Medium-High	Lab only	TRL 3–5 (Research to lab validation)

To further illustrate how these techniques can be integrated within a practical industrial setting, Figure 2 presents a schematic of a typical workflow for contaminant detection in NRC processing. The workflow demonstrates how coarse contaminants are first removed by sieving and magnetic/eddy current separation, followed by optical/NIR imaging for surface inspection, X-ray and ultrasonic systems for embedded particle detection, and finally, AI-based data integration for decision-making and process optimisation.

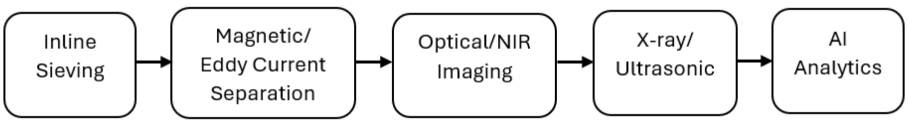

Figure 2. Industrial workflow for foreign object detection in natural rubber crumbs

VII. INDUSTRIAL CASE APPLICATION

While much of the literature on foreign object detection in natural rubber crumbs (NRC) is laboratory-based, practical implementations in industrial contexts remain limited. Nevertheless, examples from the rubber recycling sector and adjacent industries such as notably tire recycling, food inspection, and medical imaging. Table 4 reported both current adoption and transferable practices.

Table 4. Industrial and Cross-Sector Case Applications of Foreign Object Detection

Industry / Sector	Technique Used	Application	Reported Outcomes	Limitations
Crumb Rubber (Misin *et al.*, 2025)	Magnetic separation (inline)	Removal of ferrous particles during grinding	Effective for large ferrous contaminants (>100 µm); low-cost, widely used	Blind to non-ferrous and non-conductive debris
Tire Recycling (Milad *et al.*, 2020)	Recycling (Europe) Optical/NIR imaging + ML algorithms	Sorting rubber from textiles and polymer fragments	>85% classification accuracy; potential for inline	Dust interference; high hardware cost
Food Processing (Payne *et al.*, 2023)	X-ray inspection (inline, packaging lines).	Detection of metallic, glass, and stone fragments	High throughput; detects dense inclusions down to ~50 µm	High cost, uses high voltage, trouble detecting paper, wood chips, plastic, cartilage, and insects.
Food Processing (Anjali *et al.*, 2024)	AI-driven optical vision systems.	Sorting fruits/grains by shape, colour, and foreign objects	Reliable for surface-level anomalies; scalable inline use	Poor detection of embedded contaminants.
Medical Imaging (Grenier, Brun and Mellot, 2022)	CT scanning + deep learning.	Micro-anomaly detection in tissues (diagnostic imaging)	Extremely high sensitivity (<10 µm) with volumetric analysis	Very high cost; slow throughput; not industrial-ready
Medical Imaging (Origlia *et al.*, 2024)	Ultrasound with AI enhancement.	Real-time density contrast imaging in clinical diagnostics.	Effective for soft-tissue anomaly detection; adaptable for density contrast in NRC.	Limited penetration in heterogeneous matrices

VIII. IMPACT OF CONTAMINANTS ON NR PERFORMANCE

The contamination of natural rubber (NR) with foreign objects has a ripple effect on the performance, reliability, and safety of NR products. The presence of contaminants, which may vary from hard mineral pieces to metal bits and plastic wire, changes the basic characteristics of the rubber matrix to different extents. The presence of these materials is like the non-uniformity in the material that breaks the flow of material, creates areas of stress, affects the electrical uniformity, and, in most cases, is responsible for the leaching of chemicals. For this reason, the presence of these foreign materials cannot be neglected, especially when NR is used for applications that are critical for the success of the mission, such as isolation of vibrations, damping of structures, or dielectric insulation systems (Yusof & Latif, 2023).

A. Mechanical Degradation

From a mechanical perspective, contaminants compromise the stress-bearing capabilities of NR by disrupting the homogeneity of the rubber matrix. Rigid inclusions such as silica, stone fragments, or metallic debris serve as stress concentrators that promote the initiation and propagation of microcracks under tensile or cyclic loading conditions (Yusof, Latif & Yusoff, 2023). These localised defects significantly reduce tensile strength and elongation at break, particularly under dynamic conditions. Several studies have shown that even a low concentration (1–2% by weight) of non-rubber inclusions can result in a 10–25% reduction in mechanical performance indicators such as tensile modulus and fatigue life (Gehling *et al.*, 2023). In high-strain applications, these embedded particles act not only as structural flaws but also as frictional bodies that accelerate internal wear, leading to premature material failure. Furthermore, the presence of fibrous or polymeric debris interferes with filler dispersion and matrix bonding, causing mechanical anisotropy and unpredictable energy dissipation behaviour.

B. Dielectric and Electrical Failure Risks

Dielectric integrity is one of the critical aspects that contaminants affect the most, especially when NR is used in places with electric insulation or high voltage. Even metallic particles in tiny quantities can create conductive paths in the rubber matrix (Marín-Genescà *et al.*, 2023). These paths may be the ones where the charge is accumulated or micro-arcing is occurring, consequently, leading to partial discharges, electric treeing, and finally dielectric breakdown. The insulation with reduced dielectric strength becomes the weakest part of the NR components used in pads beneath electrical switchgear, substation flooring, or transformer isolation systems. Moreover, non-conductive minerals with high permittivity can influence the local electric field distribution, resulting in the material experiencing voltage gradients that are not uniform. These field enhancement effects can lead to the material suffering from heat and electrical degradation over time. The dangers from this kind of degradation are more severe in high-humidity or thermally fluctuating environments, where the contaminants can act as a barrier that allows moisture and ion transport.

C. Environmental and Leaching Concerns

Environmental safety and the long-term chemical stability of natural rubber (NR) get to be questionable in the presence of certain foreign materials. The synthetic polymer fragments, the residues of the processing lubricants, and the metallic contaminants can all together produce harmful substances under the environmental stresses, the most common of which are heat, UV radiation, and water exposure. A good example is the plasticisers that are phthalate-based, which are widely used in synthetic polymer additives and have been found to leach from surfaces derived from NR (Benjak *et al.*, 2024). On top of the aforementioned, there are metallic contaminants like zinc, lead, or chromium which are often from tire recycling or industrial scrap, that under certain conditions, e.g., wet or acidic, will slowly dissolve into the soil and groundwater causing quality risks (Rhodes, Ren & Mays, 2012). These concerns are not only environmental but also regulatory, as many regions now enforce leachate compliance thresholds through directives.

IX. CURRENT INDUSTRIAL PRACTICES AND STANDARDS

Natural rubber manufacturers and recyclers deploy a variety of quality control steps to remove contaminants before product distribution. These practices range from continuous inline screening to batch-level inspections, all guided by best-practice standards like ISO (International Organization for Standardization) and ASTM (American Society for Testing and Materials) (Vare, 2003). On the contrary, even when efforts made are considerable, variations in execution and lack of proper regulations still allow for the risk of compromising material integrity particularly in the case of high-performance or safety-critical applications.

A. Inline Screening Systems

Inline screening forms the first line of defence in contamination removal during NR processing. The NR processing usually starts with mechanical sieving, where the large particles and aggregates are removed through a multi-tiered vibratory or rotary screen system. After sieving, the magnetic drums and eddy current separators are put into play to get rid of the ferrous and non-ferrous metal fragments (Tan *et al.*, 2018). The more advanced plants may even use optical imaging systems along with RGB or NIR cameras for detecting polymeric contaminants. These visual classifiers are often further developed with machine learning models that are capable of quickly differentiating between rubber and non-rubber debris by examining their shape, size, and spectral signatures (Akinlabi, 2007). Inline systems are capable of sorting in real-time and the maximum removal efficiency they can achieve for coarse and metallic debris is 95%. On the other hand, their performance for sub-millimetre or embedded impurities is usually not very good (Tomar, Kumar & Sreejeth, 2023).

B. Batch Inspection Protocols

Following inline processing, residual NR is often conducted through batch-level quality inspections. These include X-ray or CT imaging to detect internal and embedded foreign matter that inline systems may miss. For higher precision, NR samples may undergo surface screening with ultraviolet/visible-light platforms, looking for thin polymer or lubricant films invisible to magnetic methods (Rolere *et al.*, 2015). Destructive testing methods such as sectioning crumb blocks and inspecting them under a stereomicroscope remain standard for laboratory-level analysis. Batch inspections may also include surface energy testing via IGC and chemical profiling via FTIR or Raman spectroscopy to confirm the absence of polymer, lubricant, or plastic residues (Sadeghi & Toiserkani, 2023). Together, these inspection methods provide a comprehensive understanding of contamination but are slower and less scalable than inline systems.

C. Relevant ISO and ASTM Standards

There are different industrial standards to assist quality control in rubber manufacturing but not a single framework to rule contamination limits in natural rubber (NR) specifically. Nevertheless, ISO and ASTM standards are giving methods and procedural guidance that are all relevant for the detection, quantification, and removal of foreign material. Current rules and standards provide the necessary support for quality and reproducibility in NR production and testing:

- ASTM D2000-08 that classify in selecting appropriate rubber materials and specifying them to avoid sub-standard materials, thereby mitigating the risk of foreign material contamination (Tones, Mattina & Drago, 2011; Palecek, 2014).
- ASTM D5289 were used for optimising the curing process of rubber, which can help in reducing the inclusion of foreign materials during manufacturing (Palecek, 2014).
- ISO 17025 were mandates the evaluation of measurement uncertainty, which ensures the reliability of tests conducted to detect foreign materials in rubber (De Souza & De Andrade, 2003).
- ISO 18898 provides methods for the verification and calibration of hardness testers, ensuring accurate detection of foreign materials that may affect the hardness of rubber (Štibler & Herrmann, 2007; Stibler, Menelao & Herrmann, 2010).

There are currently no specific standards anywhere that limit contamination levels for natural rubber used in insulation and electrical applications even though relevant ISO and ASTM procedures are still available. Thus, manufacturers must depend on their own specifications and tolerances established by the specific application, which is often confirmed through testing of the product's performance.

X. LIMITATIONS AND GAPS IN DETECTION TECHNOLOGIES

Despite significant advancements in detection and characterisation methods for foreign objects in natural rubber, critical drawbacks in terms of both technology and industry use remain. Such hurdles slow down the process of building comprehensive and reliable quality control systems, especially at a mass production level, where the purity of the material is crucial to mechanical strength, dielectric performance, and even compliance with standards. The industry has made great progress in devising various methods, from mechanical sieving and magnetic separation to the use of advanced spectroscopic and imaging techniques, however, still no single one can cope with all the contamination situations that might occur in the NR processing.

One of the main reasons is that no single technique can detect all types and sizes of contaminants whereas magnetic and eddy current separators cannot remove non-conductive materials, such as pieces of plastics, fibres, or minerals (like silica) while they excel in removing metal debris. In a similar manner, though optical and near-infrared (NIR) imaging systems are very fast, and they can detect the presence of contaminants based on their colour and reflectance, they often do not perceive the ones that are hidden in the bulk or have almost the same spectral properties as the rubber. The limited resolution of most inline systems, which usually captures the contaminants larger than 0.5 mm, makes the problem even worse. Smaller inclusions, despite their potential to compromise structural integrity or dielectric properties, frequently go unnoticed. While batch-level inspection techniques such as X-ray computed tomography (CT), FTIR spectroscopy, or Raman analysis offer higher sensitivity and chemical specificity, they remain time-consuming, cost-prohibitive, and poorly suited for high-throughput environments.

Moreover, implementation hurdles remain, which extend beyond technical challenges. The high-resolution systems like hyperspectral imaging, X-ray CT, and Raman spectroscopy come with a hefty price tag plus maintenance and the adoption of these systems is being limited to small and medium-sized NR producers. The inspection with AI is very appealing but the lack of large, specifically annotated datasets related to NRC contaminants poses a problem and makes the teaching of the algorithm and their transferability difficult. Besides, the fear of scalability lingers on since many sophisticated methods cannot match the capacity of the industrial processing lines that can take hundreds of kilograms per hour. Besides, even for inline applications, NIR and ultrasonic techniques are affected by dust, material variability, and sensor fouling, limiting their long-term reliability.

Technical limitations aside, the disunity of the detection strategies and the lack of standardised frameworks intensify the issue of quality control. In several industrial environments, the different detection approaches do not interact with each other and are all treated separately, leading to duplicated efforts and waste of time. Besides, the progress made in artificial intelligence and machine learning skills for pattern recognition and defect classification in other materials sectors has not yet reached the NR detection area which is still rather limited and unoptimised. Such inferiority is intensified by the absence of globally adopted standards that specify the allowable contaminant limits for different NR uses. Although ISO 2393 and ASTM D297 give the general rubber testing guidelines, they do not mention contaminant tolerance or detection methods for NRC. The absence of reference calibration materials tailored to NR hinders reproducibility and inter-laboratory consistency, making it difficult to benchmark quality across suppliers.

In short, the principal drawbacks in NR contaminant detection are linked to the exorbitant prices of high-resolution techniques, the lack of enough data for AI-powered systems, the uncertainty in regulations about the contaminant limits, and the restriction of high-throughput detection techniques to real-time usage. Winning over these challenges would mean integrating methods, creating open NR contaminant datasets, advancing real-time data analytics, and implementing global standards tailored for recycled rubber systems.

XI. ADVANCES IN AUTOMATED AND AI-BASED INSPECTION

Traditional techniques used to detect and eliminate foreign objects contaminating natural rubber (NR) often suffer from limited sensitivity, dependence on manual inspection, and reduced adaptability under variable industrial conditions. Recent advances in automated and artificial intelligence (AI)-based inspection systems have significantly transformed quality control by enabling real-time contaminant detection, high-throughput operation, and automated decision-making. The increasing application of NR in areas such as seismic isolation systems, transportation infrastructure, and electrical insulation has further intensified the demand for intelligent and adaptive inspection platforms.

Modern AI-based inspection systems improve detection reliability by integrating multiple sensing modalities, including optical imaging, hyperspectral analysis, acoustic sensing, and electromagnetic measurements. High-resolution imaging combined with convolutional neural networks (CNNs) enables classification of surface-level contaminants according to shape, texture, colour, and reflectance characteristics. Unlike conventional rule-based approaches that rely on predefined thresholds, AI-based systems learn discriminative features directly from large datasets, allowing improved differentiation between material variability and contamination events. For embedded or subsurface defects, machine learning algorithms have increasingly been applied to interpret sensor outputs from ultrasonic probes, X-ray systems, and microwave sensing platforms, reducing false detection and improving inspection consistency.

Predictive analytics and process automation have also emerged as key components of smart manufacturing environments. Digital twin frameworks representing virtual NR processing systems provide opportunities to simulate contamination scenarios, evaluate sensor configurations, and generate synthetic datasets for training AI classifiers under controlled conditions.

Evidence from other industries further demonstrates the transferability of AI-assisted inspection systems to NR applications. In the food industry, CNN-based X-ray inspection systems have been successfully deployed in conveyor-based production lines to detect contaminants such as metal fragments, plastic particles, glass, and stones under high-speed operating conditions. These systems maintain high detection accuracy despite noisy backgrounds and variable product characteristics, demonstrating the practical feasibility of AI-assisted inspection under industrial constraints. Similarly, in the polymer recycling industry, hyperspectral imaging integrated with machine learning algorithms has been widely employed for automated classification and sorting of polymers such as PET, PP, and PVC. These systems enable real-time identification of visually similar materials and contaminants that are difficult to distinguish using conventional approaches. Such examples are directly relevant to NR processing, as contaminants often exhibit physical characteristics similar to the surrounding rubber matrix, including comparable optical properties and density profiles.

Additional evidence can also be observed in medical imaging applications, where multimodal AI systems integrating ultrasound and X-ray modalities have demonstrated improved anomaly detection within complex biological tissues. These developments suggest that similar sensor-fusion strategies combining microwave, optical, ultrasonic, and X-ray sensing could be adapted to NR inspection environments where contaminant characteristics vary substantially in terms of morphology, size, and composition.

Despite these advances, several challenges remain. AI-based systems require extensive high-quality training datasets, which are often difficult to obtain due to industrial confidentiality and limited contaminant databases. Moreover, explainable AI frameworks are increasingly needed to improve transparency and support engineering decision-making, particularly in safety-critical or regulatory contexts. Cost and deployment scalability also remain significant barriers, as many AI-assisted inspection systems are still restricted to laboratory or pilot-scale implementation. Nevertheless, continued advances in computational capability and sensor-fusion technologies are expected to establish AI-driven inspection as a key component of next-generation NR quality assurance systems, supporting improved standardisation, traceability, and sustainability.

XII. FUTURE PERSPECTIVES AND RESEARCH RECOMMENDATIONS

The future quality control, however, will not just depend on this slow but steady and sure transition but rather on high-tech operations in the detection and classification of all contaminants. The integrity, safety, and environmental compliance of NR-derived products require a complete change of attitude from the classical, offline quality assessment to the modern, proactive, integrated, and intelligent quality assurance frameworks. The future research must tackle not only the technological bottlenecks but also the systemic challenges that the industry faces in terms of the detection's effectiveness, scalability, and standardisation.

A hybrid detection system that incorporates various methods into one smooth platform is the foremost area where improvement is needed such as the combination of optical and X-ray imaging along with spectroscopic techniques like FTIR or Raman can offer necessary information regarding both the physical and chemical aspects of pollutants. These types of systems with different modalities, particularly when they are supported by AI-based analytics, may become much more sensitive and selective over a broader spectrum of foreign materials, ranging from metals and minerals through to plastics and organic residues. Also, through research, the miniaturisation and industrial ruggedness of high-resolution detection tools, such as portable Raman or micro-CT scanners, should be explored for direct use on production lines without the need to compromise on throughput.

Another significant research involves the development of standard contaminant taxonomies and benchmark datasets. The absence of a commonly recognised classification for contamination in natural rubber not only makes it impossible to measure results from different laboratories against each other but also stops the training of strong machine learning algorithms. Having the same, free-to-use collections of spectra, images, and mechanical impact profiles of contaminants would help in creating predictive inspection models and making regulations more uniform. Moreover, digital twin models and simulation platforms should be established to imitate NR processing settings, allowing safe trials of new inspection methods and the optimisation of algorithms before they are used in industries.

In addition, the economic and environmental aspects of detection and remediation should be included in the life cycle assessments (LCAs) of NR products. Furthermore, research and development of detection and remediation methods that are economically viable and beneficial for the environment should be conducted. Moreover, the industry, regulators, and academia will have to be cooperating stakeholders in the development and acceptance of technological innovations as day-to-day, large-scale, practical solutions. The purity that is required for recycled materials is getting higher and this is needed in all sectors; Therefore, it is better to invest in advanced detection and characterisation research as it will ensure the unlocking of the full potential of NR in modern engineering applications.

XIII. SUMMARY AND CONCLUSION

In conclusion, there are the foreign object contaminants which drastically threaten the performance, reliability and even the safety of NR. The entry of these contaminants into the NR production process has many points. They can come along with the feedstock in such a fine form that regular detection is nearly impossible or they might be introduced at the very beginning of the sourcing, grinding, and handling to storage stages. In this review, we trawled through the existing methods which can detect and analyse these contaminants from mechanical sieving and magnetic separation to the use of optical/NIR imaging, X-ray CT, ultrasound, and spectroscopy. All these techniques have their strengths but also several drawbacks. Among them are non-sensitivity to non-metallic inclusions, resolution limits for inline systems, and lack of fully integrated detection architectures. Problems that have plagued NR for a long time like mechanical wear out, dielectric failures, and environmental safety can be made worse by contaminants that are not detected giving the need for more accurate quality control. Besides, future research should also consider how the detection system will help meet the sustainable material recovery and circular economy goals. The continual breaking down of existing limitations and the merger of different technologies will make it possible for the rubber recycling industry to quit making high-purity, high-performance NR materials suitable for very demanding applications in infrastructure, energy, and transport.

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