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Electrical Capacitance Tomography for Multiphase Flow Monitoring in Palm Oil Processing: Advances, Challenges, and Industrial Opportunities

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ABSTRACT

Multiphase flow monitoring remains a major challenge in palm oil processing, particularly for oil–water separation, product quality control, and process optimization. Electrical Capacitance Tomography (ECT) is a non-invasive, radiation-free technique that enables real-time visualization of permittivity distributions within opaque multiphase systems. Recent developments in sensor design, sensitivity modeling, and machine learning-based image reconstruction have improved imaging accuracy, noise tolerance, and computational efficiency. However, industrial adoption in palm oil mills remains limited by low dielectric contrast, calibration drift, sensor fouling, scale-up constraints, limited field validation, and difficulties in integrating ECT with existing control systems. This review critically evaluates recent developments in ECT and their applicability to palm oil processing. It compares ECT with alternative monitoring techniques, examines experimental and pilot-scale implementations, and identifies key technical, operational, and economic barriers to industrial deployment. Attention is given to machine learning-assisted reconstruction, digital twins, Industry 4.0 integration, cybersecurity, data communication, interoperability, and commercialization requirements. The review also discusses machine learning, digital twins, Industry 4.0 integration, and commercialization requirements. A conceptual implementation pathway is proposed based on published laboratory, pilot-scale, and industrial studies. The findings provide a practical reference for researchers, technology providers, and mill operators seeking to advance ECT from laboratory development towards reliable, real-time monitoring and intelligent process control.

Keywords: Electrical capacitance tomography; non-destructive monitoring; multiphase flow measurement; palm oil processing; Industry 4.0 integration

INTRODUCTION

The transition towards sustainable industrial systems has increased the demand for real-time, non-invasive monitoring technologies. These technologies can improve operational efficiency while reducing environmental impact (Abrar et al. 2021; Spille et al. 2021; Kłosowski et al. 2023). These developments align closely with the United Nations Sustainable Development Goals (SDGs) 2030, particularly SDG 9 (Industry, Innovation, and Infrastructure) (Mosorov et al. 2020; Banasiak, Bujnowicz & Fabijańska 2024), SDG 12 (Responsible Consumption and Production) (Fiderek et al. 2022; Przysucha et al. 2023; Zhan et al. 2023), and SDG 13 (Climate Action) (Kowalska et al. 2019a; Przysucha et al. 2023; Sharifi et al. 2024). In this context, non-destructive evaluation (NDE), a class of measurement techniques that enable the inspection and characterization of materials or processes without causing damage or interrupting operations, has become increasingly important in industrial monitoring systems. Electrical Capacitance Tomography (ECT) has emerged as a promising NDE technique (Hasini & Che Zahari 2025). As part of the NDE 4.0 paradigm, ECT combines advanced sensing with data analytics. It enables the visualization of permittivity distributions in opaque multiphase systems without interrupting operation. Its advantages, including low deployment cost, high-speed data acquisition (DAQ), and structural robustness, provide clear benefits over optical and radioactive sensing methods in harsh industrial environments (Almutairi et al. 2020; Jaiswal et al. 2022;

Zheng et al. 2026; Wang et al. 2026). ECT supports SDG 9 by enabling digital, non-invasive monitoring to improve industrial processes. It contributes to SDG 12 by improving separation efficiency, reducing oil losses, and minimizing waste generation. Improved process control may also support SDG 13 by reducing unnecessary energy consumption and associated emissions from inefficient palm oil processing.

Despite these advancements, the adoption of ECT in agro-industrial applications, particularly in palm oil processing, remains limited. Palm oil mills represent a key economic sector in tropical regions; however, they continue to face persistent operational challenges, including inefficient phase separation, fluctuating product quality, and unquantified oil losses (Mohamad et al. 2016; Ameran et al. 2017; Ali Othman & Ronizan 2021). Conventional quality assessment of crude palm oil (CPO) relies heavily on laboratory-based analysis, which often requires several days and delays process optimization. Early studies have used ECT to monitor oil–water–sludge transitions based on dielectric contrast (Ameran et al. 2017). However, these applications have revealed several technical limitations. The main limitations include calibration instability in large-diameter pipelines and reduced sensitivity in low-dielectric-contrast emulsions. Image reconstruction also becomes more difficult under dynamic flow conditions (Mohamad et al. 2016). Addressing these limitations requires optimized sensor configurations and robust validation protocols tailored to the high-temperature and abrasive operating conditions of palm oil mills (Hamzah et al. 2018). Palm oil processing presents greater challenges for ECT than conventional multiphase systems because oil, water, sludge, steam, and fibers may coexist under variable operating conditions. Low dielectric contrast between oil-rich and emulsified phases reduces image sensitivity, while fouling, abrasion, and temperature fluctuations can cause calibration drift. Variations in feed composition and equipment geometry also limit the use of a single calibration model across different processing stages.

Global research interest in ECT continues to expand. Between 2015 and 2025, approximately 1248 ECT-related publications were indexed in Scopus, with major contributions originating from China, the United Kingdom, and the United States. This trend reflects the strategic importance of ECT in industrial automation and process monitoring. Foundational contributions, particularly those by Professor Wuqiang Yang in sensor design and industrial applications, have significantly shaped the development of the field (Elsevier 2026a). As industries transition toward data-driven production systems, ECT is increasingly positioned as a key enabling technology for digital transformation. Figure 1 illustrates the increasing research activity in ECT. However, despite this growth, applications remain concentrated in chemical and biomedical domains, with limited focus on agro-industrial systems such as palm oil processing.

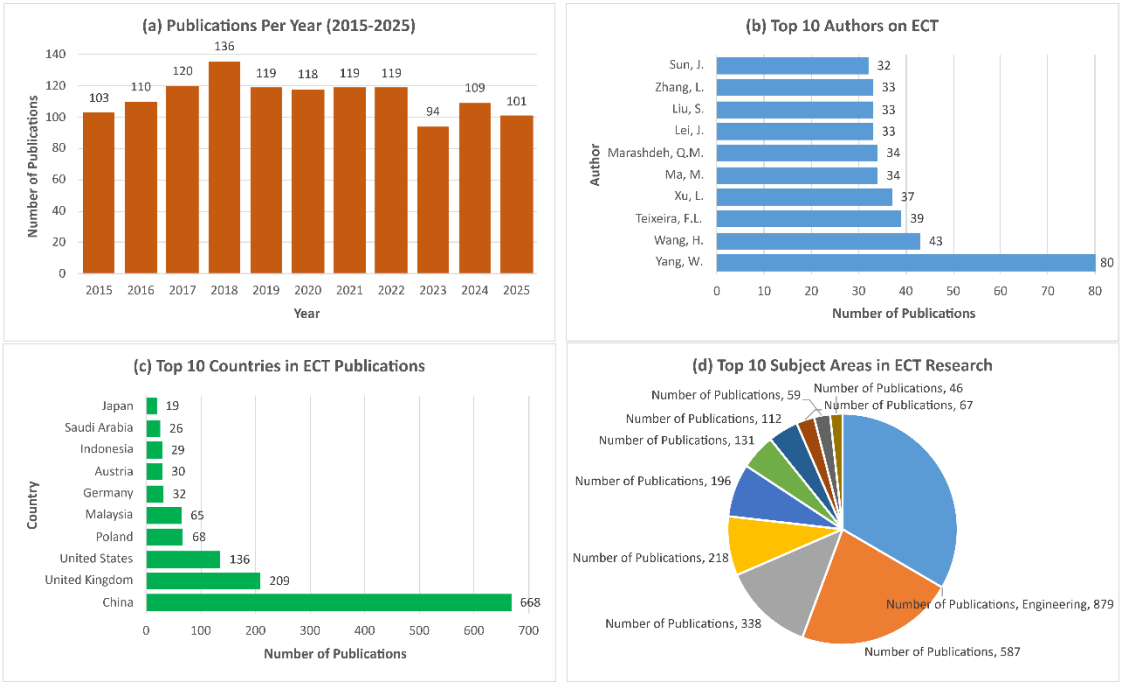


FIGURE 1. Global research activity related to ECT based on Scopus data (Elsevier 2026b). (a) Publications per year (2014–2024), (b) Top 10 most prolific authors, (c) Top 10 contributing countries, and (d) Top 10 subject areas indicating interdisciplinary research activity.

Existing review studies have primarily focused on sensor architecture and applications in conventional chemical industries. Yang (2010) and Rasel et al. (2022) emphasized the adaptability of ECT, while Wang and Yang (2021) and Poelma (2020) identified persistent challenges related to spatial resolution and calibration drift, particularly in pharmaceutical and particle-laden flow systems. Although Electrical Capacitance Volume Tomography (ECVT) extends ECT capabilities to volumetric imaging (Wang et al. 2010), its application remains limited by high computational demand. In addition, the choice of reconstruction algorithm plays a critical role in determining imaging performance. Linear approaches, such as Linear Back Projection (LBP), offer fast computation but lower resolution, whereas iterative methods improve accuracy at the expense of computational efficiency (Wang & Yang 2020). These findings indicate that, despite significant progress, achieving a balance between accuracy and real-time capability remains a key challenge for industrial deployment.

A significant knowledge gap exists in the application of ECT within agro-industrial systems, particularly in palm oil processing. Previous reviews focusing on fluidized beds (Porzuczek 2014; Ameran et al. 2016) and biomedical impedance sensing (Hope & Iles 2004; Grushko, Spurný & Černý 2020) provide limited insight into the complex multiphase conditions encountered in palm oil mills. To date, no comprehensive review has critically evaluated the application of ECT specifically for palm oil processing, where continuous monitoring is essential to minimize effluent losses and improve separation efficiency (Mohamad et al. 2016; Ameran et al. 2017; Ali Othman & Ronizan 2021). As shown in Table 1, although ECT has demonstrated significant potential across multiple domains, most studies remain limited to laboratory or pilot-scale investigations, with very few addressing full-scale industrial implementation in agro-industrial environments (Poelma 2020). Notably, none of the reviewed studies explicitly addresses the operational complexities of palm oil milling systems.

TABLE 1. Summary of ECT and related tomography applications across industrial and biomedical systems (2004–2022). The table highlights performance characteristics and limitations, underscoring the lack of field-scale implementation in agro-industrial processes such as palm oil milling.

Year	Domain/Application	Key advantage	Major limitation	Reference
2004	Electrical impedance scanning for biomedical (breast lesion detection)	Demonstrated high sensitivity for small lesions; non-invasive and low-cost screening	Poor specificity and limited three-dimensional (3D) reconstruction capabilities	(Wang & Yang 2020)
2010	3D ECVT development	Introduced scalable real-time volumetric imaging	High computational load due to the nonlinear inverse problem	(Porzuczek 2014)
2010	ECT in multiphase flow in fluidized beds	Demonstrated visualization and fault detection in industrial dryers/reactors	Calibration instability and limited spatial resolution	(Wang & Yang 2021)
2014	ECT in fluidized bed reactors for temperature and phase monitoring	Proposed multimodal tomography with infrared tomography integration	Resolution degradation under dynamic conditions	(Abd. Rahman et al. 2015)
2015	Comparison of electrical tomography techniques	Highlighted ECT as a non-invasive visualization benefit for process safety	Limited analysis of ECT-specific weaknesses and future needs	(Grushko, Spurný & Černý 2020)
2016	Cross-sector industrial and biomedical monitoring	Expanded ECT to diverse sensing applications	Limited industrial adoption due to complexity and a lack of standardization	(Yao & Takei 2017)
2017	ECT in powder–fluid interaction monitoring	Enabled real-time solid dispersion analysis	Sensor noise and resolution loss in dense media	(Ameran et al. 2017)
2017	Comparison of ECT and Electrical Impedance Tomography (EIT) for flow monitoring	Compared LBP and neural-network-based reconstruction performance	Limited speed and adaptability in rapidly changing systems	(Wang et al. 2010)
2020	ECT in particle-laden industrial flow	Tracked concentration profiles during mixing	Limited 3D accuracy	(Wei, Qiu & Primrose 2016)
2020	Prosthetic and clinical biosensing	Demonstrated potential for hybrid biofeedback systems	Limited clinical validation and reconstruction specificity	(Hope & Iles 2004)

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2020	ECT in pharmaceutical process control	Demonstrated inline monitoring in granulation and coating processes	Calibration drift and difficulty in interpreting complex multiphase interactions	(Mohamad et al. 2016)
2021	Machine learning (ML)-augmented ECT algorithms	Showed improved reconstruction robustness via ML	Basic algorithms are still sensitive to environmental effects	(Poelma 2020)
2022	Combination of ECVT with Artificial Intelligence (AI) for energy systems	Integrated data-driven volumetric flow prediction	Depending on oversimplified flow assumptions	(Rasel et al. 2022)

Recent advancements indicate promising pathways to address these limitations. Pilot-scale studies have demonstrated ECT's capability to characterize stratified CPO–sludge flows and estimate impurity levels in real time, thereby reducing reliance on manual sampling (Ameran et al. 2017; Rashid et al. 2017; Xu et al. 2020). Furthermore, integrating ECT with emerging computational approaches, including ML, Convolutional Neural Networks (CNNs), and Digital Twin (DT) frameworks, enables enhanced image reconstruction and predictive process monitoring (Wang et al. 2022; Przysucha et al. 2023; Montilla et al. 2024). In addition, recent hardware innovations, such as 3D-printed sensors and invasive electrode designs, have expanded the applicability of ECT in complex industrial environments (Ibrahim, Ahmad & Taha 2018; Botha, Conradie & van der Merwe 2026; Liu et al. 2026). Unlike previous ECT reviews that mainly focus on sensor design, reconstruction algorithms, fluidized beds, pharmaceutical processing, or general multiphase-flow applications, this review specifically evaluates ECT for palm oil processing. It critically examines sensor configuration, dielectric sensitivity, image reconstruction, pilot-scale applications, and industrial deployment challenges under palm oil mill conditions. The main contribution of this review is the identification of palm-oil-specific research gaps and the development of a conceptual pathway for field-scale implementation and Industry 4.0-enabled process monitoring.

The literature was identified through Scopus, Google Scholar, and ScienceDirect using keywords such as "electrical capacitance tomography," "ECT multiphase flow," "palm oil monitoring," "oil–water separation," and "ECT image reconstruction." Studies published mainly between 2010 and 2026 were considered, together with relevant foundational studies. Articles were included if they addressed ECT sensor design, reconstruction methods, multiphase-flow monitoring, palm oil processing, or industrial deployment. Studies unrelated to industrial ECT, lacking sufficient technical information, or reporting duplicated findings were excluded.

EVOLUTION OF TOMOGRAPHY TECHNIQUES

FROM MEDICAL IMAGING TO INDUSTRIAL PROCESS TOMOGRAPHY

The development of modern process tomography can be traced back to medical imaging, beginning with Roentgen's discovery of X-rays in 1895, which enabled the non-invasive visualization of internal biological structures (Abd. Rahman et al. 2015). Technologies such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) achieved widespread adoption in the 1970s and 1980s due to their ability to provide high-resolution anatomical imaging. However, their application in industrial environments has been limited by high equipment costs, safety concerns, and restricted adaptability to dynamic process conditions. Medical imaging systems are mainly designed for relatively stable physiological environments. Therefore, they may not be suitable for rapidly changing multiphase flows in chemical, energy, and agro-industrial processes. In addition, the use of ionizing radiation in X-ray and gamma tomography introduces strict regulatory and operational constraints. MRI systems are also limited by their dependence on hydrogen nuclei, restricting their applicability across diverse industrial materials (Wei, Qiu & Primrose 2016; Poelma 2020; Wang et al. 2022).

These limitations have driven the development of alternative imaging techniques that are safer, more cost-effective, and capable of capturing fast transient behavior in opaque systems. ECT emerged in the late 1980s as a suitable solution, enabling non-invasive monitoring of dielectric permittivity distributions with temporal resolutions exceeding 100 frames s^{-1} (Wang et al. 2010; Wang & Yang 2020, 2021). By measuring variations in boundary capacitance, ECT enables real-time visualization of gas–liquid interfaces, bubble dynamics, particle transport, and oil–water separation under industrial conditions (Yang 2010; Wang & Yang 2021). This transition represents a significant paradigm shift from static medical imaging toward dynamic, real-time industrial diagnostics.

Over time, ECT has been successfully applied in fluidized bed reactors (Agu et al. 2019), oil and gas systems (Yang 2010), pneumatic conveying (Wang & Yang 2021), silo discharge monitoring (Waktola et al. 2018), and food processing (Gupta et al. 2018). Figure 2 illustrates this evolution, showing how principles derived from medical tomography have been adapted into monitoring tools that support sustainable process control, including applications in palm oil processing. This evolution highlights the shift from high-resolution but static imaging systems toward robust, real-time monitoring solutions required in industrial multiphase processes.

ADVANCEMENT AND COMPARATIVE EVALUATION OF TOMOGRAPHIC AND SENSING MODALITIES

With the advancement of process tomography, electrical-based modalities such as ECT, EIT, and Electrical Resistance Tomography (ERT) have emerged as preferred tools for non-invasive diagnostics in complex industrial systems due to their robustness and cost-effectiveness (Kowalska et al. 2019b; Neumayer et al. 2024a, 2024b). ECT is particularly suitable for monitoring non-conductive dielectric media, such as gas–solid and oil–water systems, offering a high temporal resolution of up to 1,000 frames s^{-1} with externally mounted electrodes that do not interfere with the process flow (Kowalska et al. 2019b). In contrast, EIT and ERT are more suitable for conductive environments, including wastewater treatment and electrochemical reactors, where impedance or resistance variations reflect compositional changes (Neumayer et al. 2024a, 2024b). Compared with medical imaging modalities such as X-ray, CT, and MRI, electrical tomography techniques are more portable, cost-effective, and safer, as they do not rely on ionizing radiation and are suitable for continuous monitoring in opaque industrial systems (Poelma 2020; Ivanenko et al. 2024). Optical imaging (Townsend et al. 2019) and infrared thermography (Wang & Yang 2020) are generally unsuitable for opaque multiphase systems because they depend on line-of-sight access. Ultrasonic tomography (Poelma 2020), although capable of detecting phase interfaces, is often limited by complex transducer alignment and slower data processing.

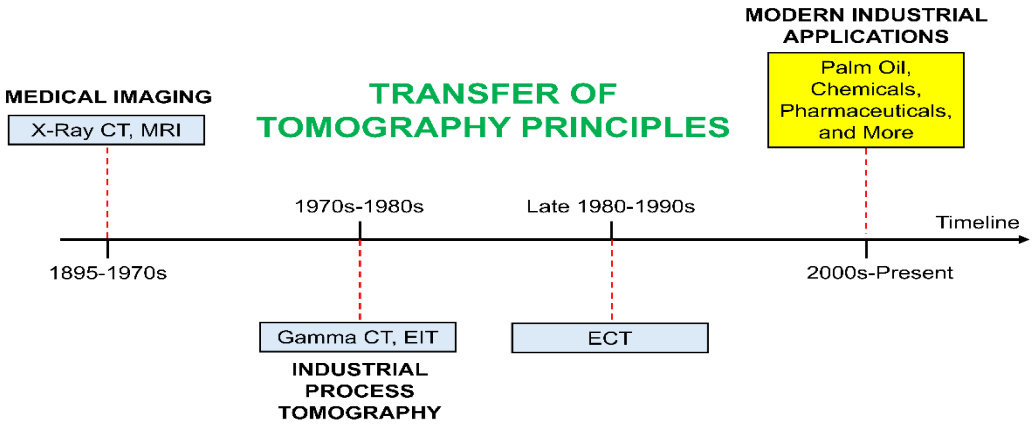


FIGURE 2. Evolution of tomography techniques from medical imaging (X-ray, CT, MRI) to industrial process tomography, highlighting the transition toward real-time, non-invasive monitoring technologies such as ECT for dynamic multiphase systems.

Although EIT and ERT can provide higher spatial resolution in conductive media, they typically lack the temporal responsiveness required for rapidly evolving multiphase flows. Table 2 compares ECT with alternative monitoring techniques based on their main advantages, limitations, relative cost, response time, and suitability for industrial deployment. Each modality involves trade-offs between spatial resolution, temporal resolution, and hardware complexity. ECT is distinguished by its high temporal resolution and relatively simple instrumentation, making it suitable for dynamic systems such as pipelines and fluidized beds (Kowalska et al. 2019b). Although ECT has reached moderate to high readiness in several industrial sectors, its readiness for palm oil processing remains lower because full-scale validation, standardized calibration, fouling control, and long-term field performance have not yet been established. EIT offers moderate spatial resolution for biomedical and electrochemical applications (Yao & Takei 2017), while ERT is optimized for highly conductive fluids (Neumayer et al. 2024b). To address the inherent spatial resolution limitations of ECT, multimodal approaches have been explored. Porzuczek (2014) demonstrated that combining ECT and ERT improves material discrimination capability. More recently, ML-based reconstruction techniques have reduced imaging artifacts and improved quantitative accuracy, supporting

the transition toward adaptive and closed-loop process control. These developments are aligned with Industry 4.0 and DT frameworks, enabling predictive maintenance and data-driven optimization (Król et al. 2023). This capability is particularly relevant to palm oil processing, where continuous, non-invasive monitoring is required to improve oil–water separation efficiency and reduce effluent losses. Overall, ECT offers lower cost, faster response, and safer continuous operation than X-ray, CT, and MRI, but with lower spatial resolution. Therefore, ECT is more suitable for real-time process monitoring than for high-resolution inspection. Its main advantage over EIT and ERT is its suitability for non-conductive media, although its performance decreases when the dielectric contrast between phases is low.

TABLE 2. Comparison of ECT and alternative monitoring techniques for industrial multiphase-flow applications.

Technique	Main advantages	Main disadvantages	Relative cost	Typical response time	Industrial readiness
ECT	Non-invasive, radiation-free, high-speed, and suitable for opaque media	Limited spatial resolution and reduced sensitivity at low dielectric contrast	Low	Millisecond-scale; real-time	Moderate to high for general industrial monitoring; low to moderate for palm oil mills
EIT/ERT	Suitable for conductive fluids and relatively simple instrumentation	Requires electrical contact and is unsuitable for non-conductive materials	Low to moderate	Milliseconds to seconds	High for conductive liquid systems
X-ray/CT	High spatial resolution and clear phase-boundary detection	Ionizing radiation, strict safety requirements, and complex equipment	High	Seconds to minutes	Moderate; mainly for controlled or specialized applications
MRI	High-resolution imaging without ionizing radiation	High cost, large equipment, and limited material compatibility	Very high	Seconds to minutes	Low for routine industrial deployment
Ultrasonic tomography	Non-invasive and capable of detecting internal interfaces	Sensitive to transducer positioning, acoustic properties, and signal attenuation	Moderate	Milliseconds to seconds	Moderate
Optical/infrared imaging	Fast response and simple image interpretation	Requires optical access and is unsuitable for opaque vessels or pipelines	Low to moderate	Millisecond-scale; real-time	Low for opaque multiphase systems

ELECTRICAL CAPACITANCE TOMOGRAPHY (ECT)

WORKING MECHANISM, SYSTEM COMPONENTS, AND ELECTRODE CONFIGURATION

ECT is a non-invasive imaging technique that reconstructs permittivity distributions within a vessel by measuring capacitance variations between multiple electrodes arranged around the sensing domain (Hamzah et al. 2018). When an excitation voltage is applied to a transmitting electrode, the resulting electric field interacts with the dielectric properties of materials inside the vessel. Adjacent electrodes detect the resulting field perturbations, and a complete dataset is obtained by sequentially measuring all electrode pairs (Yang 2010). As illustrated in Figure 3, capacitance measurements are obtained sequentially between electrode pairs, forming a dataset that is subsequently processed for image reconstruction. A typical ECT system consists of three main components (Majchrowicz et al. 2020): (i) a capacitive electrode array with shielding to minimize electromagnetic interference, (ii) a high-speed DAQ system responsible for signal excitation, demodulation, and digitization, and (iii) an image reconstruction unit that estimates material distribution within the sensing domain. Electrode configuration plays a critical role in determining system performance. Increasing the number of electrodes generally improves spatial resolution; however, it also increases system complexity, calibration requirements, and sensitivity to environmental noise. Additional factors, including electrode length, placement, sensor geometry, and vessel wall thickness, significantly influence measurement sensitivity and electric field uniformity

(Chang et al. 2023). Sun et al. (2019) demonstrated that increasing the electrode count from 8 to 16 enhances spatial resolution but requires improved shielding and optimized grounding to maintain signal stability in industrial environments. Permittivity distribution refers to the spatial variation in a material's ability to store electrical energy within the sensing region. Different materials or phases produce different permittivity values, allowing their locations and distributions to be estimated from capacitance measurements.

Sensitivity modeling determines how a change in permittivity at each location affects the capacitance measured between electrode pairs. The resulting sensitivity matrix is then used to reconstruct the material distribution within the sensing region. Sensitivity distribution modeling, typically conducted using the Finite Element Method (FEM), produces a sensitivity matrix that describes the relationship between permittivity variations and measured capacitance. This matrix serves as the basis for the inverse reconstruction problem. Early reconstruction techniques, such as LBP, provide rapid visualization but limited quantitative accuracy. In contrast, iterative methods, including Landweber and Conjugate Gradient Least Squares approaches, improve image fidelity at the expense of higher computational cost. Recent advances in ML-based reconstruction, particularly CNNs, have enabled higher-resolution imaging with improved robustness under noisy, dynamic, multiphase flow conditions (Hamzah et al. 2018). These developments support real-time monitoring of gas–liquid, solid–liquid, and oil–water systems for flow regime identification, phase fraction estimation, and separation performance analysis (Mohamad et al. 2013; Hamzah et al. 2018). The modular design of ECT hardware allows deployment in circular pipelines, vertical clarifiers, and irregular vessel geometries commonly encountered in palm oil processing. When integrated with embedded computing and Industry 4.0 architectures, ECT functions as a scalable, radiation-free, and cost-effective platform for intelligent process monitoring and adaptive control.

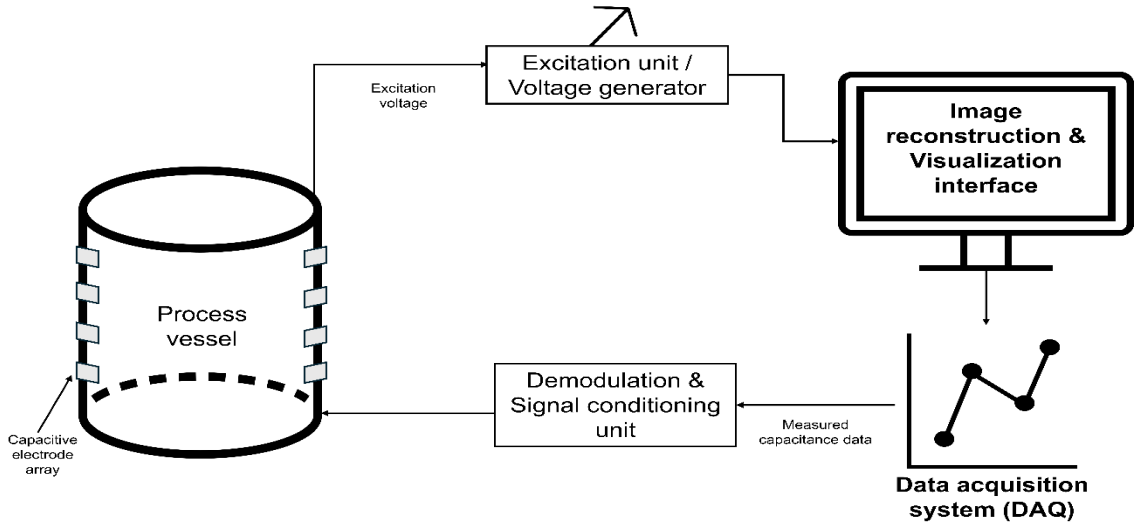


FIGURE 3. Schematic illustration of an ECT system showing the electrode array configuration, capacitance measurement sequence, data acquisition unit, and image reconstruction workflow used for multiphase flow monitoring.

DIELECTRIC SENSITIVITY AND CHALLENGES IN MULTIPHASE MATERIAL VISUALIZATION

Dielectric sensitivity in ECT refers to the ability of the system to translate variations in the material permittivity within the sensing region into measurable changes in electrode capacitance. This relationship is fundamental for visualizing multiphase flow behavior in opaque systems where direct observation is not feasible. However, when the permittivity contrast between phases is low, as in palm oil–water emulsions, image reconstruction becomes challenging. This often leads to blurred phase boundaries and reduced accuracy in detecting sharp interfaces (Ameran et al. 2016; Chang et al. 2023). Quantitative comparisons also demonstrate the effect of reconstruction algorithms on ECT image quality. For four representative flow patterns, LBP produced image errors of 37.64–83.82% and correlation coefficients of 0.36–0.74, whereas Landweber reduced the errors to 23.08–35.68% and increased the correlations to 0.72–0.90 (Hamzah et al. 2018). These results provide a useful performance benchmark for ECT applications where low dielectric contrast makes phase boundaries difficult to distinguish. The presence of emulsified droplets, transient mixing regions, and gradual

permittivity gradients further distorts the electric field distribution, amplifying the inherent soft-field limitation of ECT. As a result, interfacial curvature may be overestimated, and the detection of fine structures, such as small bubbles or dispersed droplets, becomes limited in turbulent or highly mixed conditions (Perera, Amaratunga & Time 2018). To address these limitations, FEM-based sensitivity modeling (Wanta, Smolik, et al. 2022) and advanced electrode sensor models (Wajman 2021) have been developed to improve field distribution prediction and forward model accuracy. Studies by Kowalska et al. (2019a) and Zhao et al. (2024) show that modifying electrode shape, spacing, and wall thickness can enhance sensitivity in central regions of the domain, although this increases computational and fabrication complexity. Hardware innovations have also improved ECT performance in industrial environments (Hamzah et al. 2024). These include miniaturized embedded sensors, invasive electrode configurations, and 3D-printed thin-wall sensors (Kowalska et al. 2019b). In palm oil mills, temperature changes can alter material permittivity and baseline capacitance, resulting in calibration drift. Oil, sludge, and fibrous deposits on the pipe wall or sensor surface may also reduce sensitivity and produce image artifacts. Abrasive solids may further damage protective layers and affect long-term sensor stability. These effects can be reduced through temperature compensation, protective sensor linings, routine cleaning, reference measurements, and periodic recalibration under actual operating conditions.

In parallel, advances in reconstruction algorithms, particularly ML-based approaches, have improved ECT performance in low-contrast systems. Models based on CNNs and Generative Adversarial Networks (GANs) demonstrate enhanced edge detection, noise suppression, and reconstruction stability compared to traditional iterative methods. Recent studies show a shift towards faster and more physically informed reconstruction models. Wanta et al. (2024) demonstrated real-time nonlinear ECT reconstruction using a generative adversarial network. Peng et al. (2025) reviewed recent deep learning approaches and identified dataset quality, model generalization, and physical consistency as key challenges. Liu et al. (2026) further combined sparse priors with physics-guided deep learning to improve reconstruction consistency. However, further validation using representative industrial data remains necessary. However, ML-based reconstruction requires large, representative training datasets, which remain limited for palm oil processing conditions. Models trained using simulated or laboratory data may not perform consistently under changes in temperature, flow regime, material composition, sensor geometry, and measurement noise. The computational demand for model training and high-speed image reconstruction may also limit real-time deployment on standard industrial hardware. Therefore, model validation, domain adaptation, and efficient computing platforms are required before reliable field implementation (Sun et al. 2019). Beyond single-modality sensing, hybrid approaches such as displacement current phase tomography and techniques that leverage Maxwell–Wagner–Sillars polarization effects provide complementary conductivity information, improving performance in highly emulsified or water-rich systems (Rasel et al. 2022). As summarized in Table 3, ECT has been widely applied across diverse industrial sectors, primarily for the visualization and monitoring of multiphase flow behavior. However, most applications focus on controlled environments such as fluidized beds and pipelines, where flow conditions are relatively predictable. In contrast, complex agro-industrial systems, such as palm oil milling, involve highly variable multiphase interactions, temperature fluctuations, and emulsified phases, which are insufficiently addressed in existing studies. Notably, while ECT demonstrates versatility across multiple domains, its application in palm oil processing is limited to specific stages, underscoring the need for broader integration across the full processing chain. Overall, advancements in dielectric modeling, sensor design, and reconstruction algorithms continue to expand ECT's capabilities for real-time, high-resolution monitoring of complex multiphase systems. These improvements are particularly important in palm oil processing, where accurate visualization of oil–water–sludge interactions directly influences product quality, recovery efficiency, and environmental performance.

TABLE 3. Representative industrial applications of ECT, highlighting its functional roles in multiphase flow diagnostics, material visualization, and process monitoring across diverse sectors.

No	Application domain/ Industry	Primary role of ECT	References
1	Fluidized bed reactors	Visualization of bubble dynamics and gas–solid interaction behavior	(Agu et al. 2018; Mohamad et al. 2016)
2	Pneumatic conveying and powder flow	Monitoring powder density distribution, bridging detection, and blockage prevention	(Neumayer et al. 2023; Romanowski et al. 2020)
3	Palm oil processing	Monitoring steam/vapor distribution, oil release dynamics, and multiphase separation behavior	(Hamzah et al. 2018; Mohamad et al. 2013)

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4	Oil–water separation and crude recovery	Detecting phase separation interfaces and evaluating oil recovery efficiency	(Mohamad et al. 2013; Wang et al. 2022)
5	Gas-liquid multiphase pipelines	Identifying flow regimes and real-time transition patterns	(Fiderek, Kucharski & Wajman 2021; Lin et al. 2023)
6	Crystallization and fermentation reactors	Monitoring phase growth dynamics and supporting bioprocess optimization	(Przysucha et al. 2023; Wang et al. 2022)
7	Food manufacturing and sustainability	Assessing material uniformity and product consistency metrics	(Kowalska et al. 2019a, 2019b; Rybak & Strzecha 2021)
8	Combustion and flame diagnostics	Locating flame boundaries and analyzing combustion zone characteristics	(Ding et al. 2024; Xue et al. 2021)
9	Biomedical and soft tissue imaging	Reconstructing permittivity distribution in biological tissues	(Mosorov et al. 2020; Voß & Voß 2023)
10	Structural health or leakage monitoring	Detecting cracks, voids, or leakage pathways in engineered materials	(Wanta et al. 2022a, 2022b)

ECT IN PALM OIL PROCESSING AND RECOVERY SYSTEMS

MULTIPHASE FLOW CHARACTERISTICS AND SEPARATION ISSUES IN PALM OIL MILLS

Palm oil milling involves complex multiphase flow interactions, particularly during sterilization and oil recovery stages, where steam, oil, water, and fibrous solids coexist under highly dynamic conditions (Mohamad et al. 2013, 2016). These processes occur in opaque vessels operating at elevated temperatures and pressures, which significantly restrict visual access and complicate real-time monitoring (Wang & Yang 2020). In sterilization chambers, uniform steam distribution is essential for effective fruit softening and oil cell rupture. However, non-uniform thermal penetration can lead to incomplete sterilization, increased energy consumption, and reduced oil yield. In downstream clarification and separation units, performance is further challenged by the formation of stable emulsions and fluctuating oil–water interfaces, driven by variations in fruit moisture content, feed distribution, and thermal gradients (Mohammad Fauzi et al. 2021; Ndukwu et al. 2025). Conventional instrumentation, such as thermocouples and pressure transmitters, provides localized, time-average measurements that are insufficient to capture internal phase dynamics. In addition, laboratory-based quality assessment of CPO typically requires 2–5 days, delaying process adjustments and increasing the risk of product inconsistency and effluent loss (Ameran et al. 2017). These methods rely on manual sampling and provide only a snapshot of the process at a specific time and location. The results may not represent rapid changes in oil, water, and sludge composition during operation. Sampling, handling, and operator differences may also affect measurement consistency. Therefore, laboratory analysis is unsuitable for continuous monitoring and immediate process adjustment. Currently, no widely deployed monitoring technology in palm oil mills enables continuous, online tracking of phase composition or interface behavior within pipelines and separation vessels. This limitation represents a critical gap in process visibility and control, directly affecting oil recovery efficiency, energy utilization, and Palm Oil Mill Effluent (POME) management.

ECT offers a viable solution to this challenge by enabling non-invasive, high-speed visualization of internal phase distributions in real time. It has demonstrated the capability to monitor steam distribution, track interface movement, and detect sludge accumulation without disrupting process operation. Mohamad et al. (2013, 2016) applied portable 16-electrode ECT sensors in palm oil recovery pipelines. The sensors successfully characterized stratified and dispersed liquid–liquid flow regimes. ECT systems can operate at pressures up to 20 bar and temperatures exceeding 100°C (Neumayer et al. 2024a), with temperature-compensated calibration techniques mitigating measurement drift under fluctuating thermal conditions. Beyond two-dimensional (2D) imaging, ECVT extends these capabilities to 3D visualization, enabling volumetric estimation of phase fractions, velocity fields, and separation dynamics in clarifiers and screw press outlets (Montilla et al. 2024). However, ECVT requires significant computational resources, and its real-time implementation depends on advances in fast reconstruction algorithms and hardware acceleration. By replacing invasive probes and line-of-sight optical systems, ECT enhances process transparency, improves steam utilization efficiency, and supports predictive maintenance strategies. These improvements contribute to reduced POME generation, stabilized oil recovery performance, and alignment with sustainable milling objectives. Therefore, ECT is positioned not only as a monitoring tool but also as a scalable NDE solution tailored to the operational complexity of agro-industrial processing systems. Figure 4 illustrates the potential integration of ECT at key palm

oil processing units, including the sterilizer chamber, screw press outlet, recovery pipeline, and clarification unit. The sensor data are transferred to the data acquisition and image reconstruction system for real-time monitoring and process control. Practical ECT deployment in palm oil mills is affected by sensor fouling, calibration drift, harsh operating conditions, and maintenance requirements. Deposits of oil, sludge, and fibers on pipe walls may alter capacitance readings and reduce image accuracy. Temperature changes, vibration, moisture, and variations in feed composition may also shift the calibration baseline. Abrasive solids can damage protective sensor layers and shorten service life. These limitations require temperature compensation, protective linings, routine cleaning, reference measurements, and periodic recalibration. Installation and maintenance costs may also be high, particularly when sensors must be retrofitted to existing equipment. Therefore, industrial adoption depends on robust sensor design, accessible installation, trained operators, and clear evidence that process savings can offset capital and maintenance costs.

EXPERIMENTAL STUDIES AND PILOT-SCALE APPLICATIONS OF ECT

Industrial applications for ECT have been reported in several sectors. Neumayer et al. (2024a) applied ECT in a large-scale pneumatic conveying system to monitor material distribution under industrial operating conditions. ECT has also been used in pharmaceutical fluidized beds for process monitoring (Wang & Yang 2021) and in two-component adhesive systems to evaluate mixing quality (Voß & Voß 2023). These examples demonstrate the potential of ECT for continuous industrial monitoring but also highlight challenges related to calibration, scale-up, and process-specific sensor design. In palm oil processing, implementation remains mainly limited to pilot-scale studies and individual processing units. Several experimental and pilot-scale studies have demonstrated the feasibility of applying ECT for real-time multiphase flow monitoring in palm oil processing, addressing the longstanding need for inline diagnostics, as summarized in Table 4. As summarized in Table 4, existing ECT implementations in palm oil processing are primarily limited to specific unit operations such as screw press outlets, recovery pipelines, and sterilization chambers. While these studies demonstrate the feasibility of real-time multiphase monitoring, they remain largely confined to pilot-scale or localized deployments and offer limited integration across the full processing chain. Furthermore, current implementations primarily focus on phase visualization and qualitative assessment, with limited emphasis on quantitative control metrics and automated feedback integration.

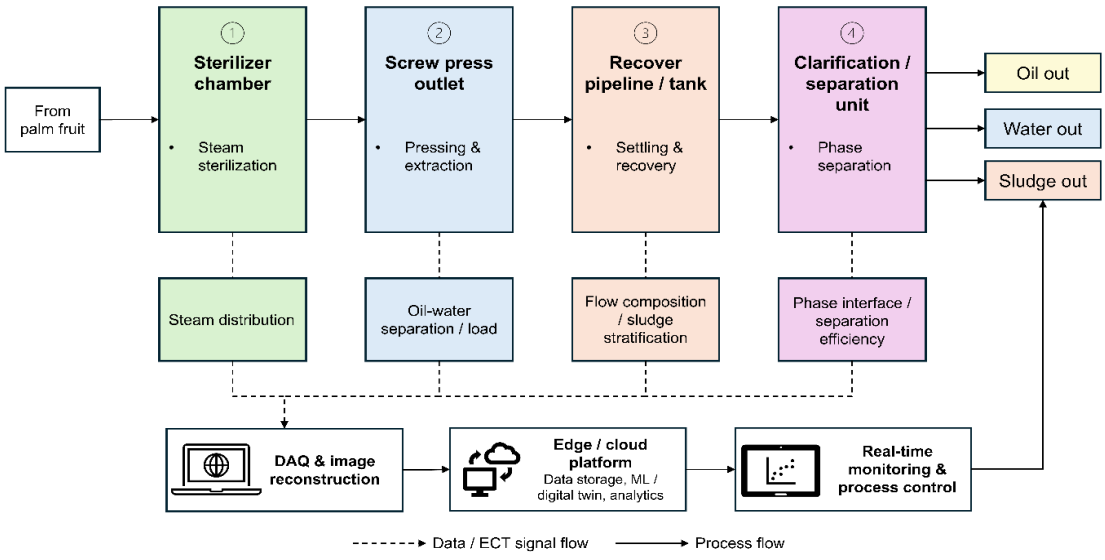


FIGURE 4. Conceptual integration of ECT in palm oil processing, showing potential monitoring locations and data flow for real-time process monitoring and control.

This indicates that although ECT has demonstrated strong diagnostic capabilities, its role in closed-loop process optimization in palm oil mills remains underdeveloped. Mohamad et al. (2013) developed a portable 16-electrode ECT sensor for visualizing CPO flow in pipelines, enabling online estimation of phase fractions, velocity distribution, and oil–water–sludge stratification, measurements that previously required up to 5 days of laboratory analysis. The portable configuration allowed installation across pipelines of varying diameters without requiring major sensor modification, making it suitable for retrofitting existing processing facilities. Gage Repeatability and Reproducibility analysis confirmed consistent measurement performance under controlled conditions, although recalibration was necessary in environments with fouling or abrasive fiber transport. Subsequent work by Mohamad et al. (2016) further characterized stratified CPO–sludge flow in horizontal pipelines and validated reconstructed phase distributions against visual cross-sectional observations. The results demonstrated improved sensitivity and measurement stability when advanced excitation techniques were applied. In addition, planar ECT sensor configurations have been implemented at screw press outlets and recovery tanks, enabling high-speed visualization of separation dynamics and sludge entrainment behavior, thereby reducing reliance on operator-dependent process adjustments.

TABLE 4. Summary of experimental and pilot-scale implementations of ECT in palm oil processing, highlighting application stage, monitoring objectives, and sensor configurations across screw press, recovery, and sterilization units.

No	Application stage	Monitoring objective	Sensor type	References
1	Screw press outlet	Oil–water separation and load waste estimation	Portable 2D planar ECT sensor	(Mohamad et al. 2013)
2	Recovery pipeline/ tank	CPO flow composition and sludge stratification	Inline ECT with tank-mounted adapter	(Mohamad et al. 2016)
3	Sterilizer chamber	Steam penetration, thermal distribution, and sterilization uniformity	Multi-electrode vertical array	(Hamzah et al. 2018)

To address challenges associated with low dielectric contrast and transient flow conditions, Hamzah et al. (2018) developed iterative reconstruction algorithms, including Landweber and Generalized Vector Sampled Pattern Matching methods, which outperform conventional LBP in terms of correlation accuracy and reconstruction error. More recently, ML-based approaches have been introduced, with CNNs and decision tree models demonstrating improved phase boundary detection and pattern recognition in emulsified flow regimes (Deabes et al. 2022). Przysucha et al. (2023) further showed that CNN-based reconstruction reduces imaging artefacts and enhances quantitative accuracy compared to traditional iterative methods. However, these approaches require large, domain-specific datasets and robust calibration strategies to ensure consistent performance under variable industrial conditions. The increasing interest in Malaysia's palm oil industry reflects growing demand for real-time monitoring systems that improve product consistency and reduce POME generation. Inline ECT systems provide a foundation for Industry 4.0-enabled feedback control, supporting adaptive operation and predictive maintenance. Collectively, these pilot-scale studies demonstrate the transition of ECT from laboratory-scale research toward practical industrial deployment, establishing it as a scalable, non-destructive monitoring solution for process diagnostics, structural assessment, and real-time control in palm oil milling operations. Although existing studies demonstrate the feasibility of ECT in palm oil processing, the available evidence remains limited to small-scale systems and selected processing units. Differences in sensor geometry, calibration methods, flow conditions, and performance metrics also prevent direct comparison between studies. Current results, therefore, confirm ECT's diagnostic potential but are insufficient to establish its quantitative reliability across different palm oil mills. The main research need is no longer proof of feasibility, but repeatable field-scale performance under variable temperature, fouling, feed composition, and operating conditions.

FUTURE DIRECTIONS AND INDUSTRIAL READINESS OF ECT

DIGITAL INTEGRATION AND PROSPECTS FOR INTELLIGENT PROCESS CONTROL

ECT is evolving from a diagnostic imaging tool into a core enabler of intelligent process control in palm oil milling, aligning with Industry 4.0 paradigms that emphasize automation, digital connectivity, and data-driven decision-making (Romanowski et al. 2020). By generating real-time, non-invasive permittivity maps, ECT enables continuous monitoring of flow regimes, phase composition, and separation efficiency under harsh and opaque operating conditions without interrupting production (Mohamad et

al. 2013). This represents a substantial improvement over conventional verification methods for CPO quality, which rely on laboratory-based analyses that may require several days and delay process optimization (Kowalska et al. 2019a; Król et al. 2023). Recent developments integrate ECT with ML, enhancing reconstruction and interpretation processes with CNNs and GANs. These approaches enable automated recognition of flow patterns and improved phase boundary delineation in oil–water separation systems. For example, GAN-based reconstruction has been shown to enhance boundary sharpness and reduce artifacts that can otherwise lead to misclassification during process monitoring (Wanta et al. 2024). ML-enhanced ECT systems further support predictive analytics by identifying process anomalies, forecasting deviations, and enabling proactive optimization of operating conditions (Wang & Yang 2021).

However, the reliability of these models depends strongly on the availability of domain-specific training datasets and robust strategies for handling noise and variability in industrial environments. Emerging system architectures that integrate ECT with wireless sensor networks and cloud-based supervisory platforms enhance remote accessibility and enable cross-plant benchmarking and centralized optimization (Deabes 2019; Król et al. 2023). Industry 4.0 integration also requires secure and reliable data communication. ECT data should be protected through user authentication, access control, encryption, and secure network architecture to reduce cybersecurity risks. Standard communication protocols, such as OPC UA and MQTT, can improve interoperability between ECT systems, supervisory control platforms, and existing plant equipment. However, compatibility with legacy control systems and differences in data formats remain practical challenges for industrial deployment. In parallel, edge computing platforms, such as NVIDIA Jetson modules, allow high-throughput ECT data to be processed locally with low latency, enabling real-time closed-loop control of separation, sterilization, and recovery processes (Wang et al. 2022). Nevertheless, edge deployment introduces constraints on computational resources, requiring model compression and lightweight architectures to ensure stable field operation. Despite these limitations, digitally integrated ECT systems offer significant potential to automate process adjustments, reduce operational variability, and minimize energy consumption and effluent generation. Overall, digital integration positions ECT not only as a monitoring technology but as a foundational component of adaptive, self-optimizing manufacturing systems, addressing longstanding limitations in inline, non-destructive quality control for complex multiphase processes.

RESEARCH GAPS, STANDARDIZATION, AND A PATHWAY TOWARD FIELD DEPLOYMENT

Despite its strong potential, ECT still faces several challenges that limit widespread industrial adoption in palm oil processing environments. One of the primary barriers is the lack of standardized calibration procedures, image quality metrics, and reconstruction protocols, which hinders reproducibility and reduces confidence in system reliability. Scaling challenges also arise when the sensing domain increases, as spatial resolution decreases and electrode sensitivity is reduced, particularly under high-temperature and high-pressure conditions typical of palm oil processing systems (Wang & Yang 2021). In addition, methodological inconsistencies, including variations in sensor geometry, shielding design, sensitivity modeling, and reconstruction algorithms, make it difficult to compare system performance across studies and establish reliable benchmarking frameworks (Yang 2010; Hamzah et al. 2018; Xue et al. 2021).

Another critical limitation is the scarcity of validated ground-truth datasets for palm oil emulsions and recovery systems, which constrains the development and generalization of AI-assisted reconstruction models. To address this, the development of modular experimental testbeds and open-access benchmarking datasets is essential. These resources would enable systematic evaluation of reconstruction accuracy and algorithm robustness under controlled and reproducible conditions. As highlighted by Poelma (2020), controlled phantom experiments remain fundamental for quantifying reconstruction error and ensuring interpretability. Alignment with established standards, such as ISO 5725 and ASTM E177, could improve repeatability and reproducibility. It would also support unified performance indicators, including minimum resolvable feature size, signal-to-noise ratio, and sensitivity stability. At the same time, emerging approaches such as AI-driven calibration (Rasel et al. 2022) and predictive diagnostics (Romanowski et al. 2020) offer promising pathways to mitigate drift, accelerate reconstruction, and enable automated anomaly detection. However, these approaches require large, diverse datasets and robust domain adaptation to ensure reliable deployment under variable industrial conditions. Addressing these challenges is essential to transition ECT from a laboratory-validated technique to a fully field-ready solution for continuous, high-throughput palm oil processing. Achieving this transition will enable reliable inline quality monitoring, improved separation efficiency, and the establishment of digital infrastructure necessary for sustainable industrial adoption. These developments closely align with Industry 4.0 objectives and the broader evolution of NDE technologies toward intelligent,

integrated process-monitoring systems. These advancements collectively define a clear pathway for integrating ECT into industrial palm oil processing systems, supporting the transition from experimental validation to scalable, real-world deployment. The proposed implementation pathway consists of four stages. First, laboratory validation should assess sensor accuracy, dielectric sensitivity, calibration stability, and reconstruction performance using representative palm oil mixtures. Second, pilot-scale testing should be conducted at selected units, such as recovery pipelines, screw press outlets, or clarification tanks, under actual temperature, fouling, and flow conditions. Third, the ECT system should be integrated with existing data acquisition and plant control platforms, together with secure communication, maintenance procedures, and operator training. Finally, full-scale deployment should proceed after long-term reliability, installation and maintenance costs, process benefits, and return on investment have been demonstrated. The proposed pathway is conceptual and is based on findings synthesized from the reviewed literature rather than new experimental validation. Its effectiveness should therefore be evaluated through pilot-scale and full-scale implementation in palm oil mills.

FUTURE RESEARCH AND COMMERCIALIZATION OPPORTUNITIES

Future research should prioritize full-scale validation under actual palm oil mill conditions. Key areas include calibration stability, fouling resistance, temperature compensation, sensor durability, standardized performance assessment, and the development of representative industrial datasets for machine learning models. Research should also examine lightweight reconstruction algorithms, secure data communication, and integration with existing plant control systems.

]Commercialization opportunities include modular ECT sensors that can be retrofitted to recovery pipelines, screw press outlets, sterilizers, and clarification tanks. However, commercial adoption requires reliable long-term performance, simple maintenance procedures, operator training, and techno-economic assessment. Installation cost, sensor lifetime, cleaning frequency, recalibration requirements, process savings, and payback period should be evaluated through pilot-scale and full-scale studies. Collaboration among researchers, ECT manufacturers, automation providers, and palm oil mill operators will be essential for converting laboratory systems into commercially viable industrial solutions.

The economic feasibility of ECT depends on sensor installation, calibration, maintenance, data processing, and integration with existing control systems. These costs may be offset by reduced oil losses, fewer laboratory analyses, improved separation efficiency, and earlier detection of process faults. Modular sensors that can be retrofitted to existing equipment may further reduce installation costs. However, the actual return on investment should be assessed through field-scale studies that account for capital costs, operating savings, maintenance requirements, and the payback period. Long-term field studies should quantify sensor lifetime, cleaning frequency, recalibration intervals, maintenance cost, and production savings to determine the economic feasibility of ECT deployment.

CONCLUSIONS

This review examines the fundamental principles, recent technological developments, and the potential for industrial deployment of ECT, with particular emphasis on its applicability to palm oil processing. ECT offers significant advantages over conventional point-based sensing systems, including non-invasive operation, real-time visualization, and suitability for opaque multiphase environments. Although ECT has been widely applied in sectors such as pneumatic conveying, fluidized-bed processing, and fermentation systems, its adoption in agro-industrial applications, particularly in palm oil milling, remains limited. This review identifies several critical challenges hindering broader implementation, including limitations in spatial resolution, calibration instability, reduced dielectric sensitivity in low-contrast emulsions, and the absence of standardized performance metrics and benchmarking protocols. Recent advancements integrating ECT with AI-driven reconstruction, multimodal sensing, DT frameworks, and edge computing platforms have significantly improved image quality, anomaly detection, and real-time decision-making capability. These developments demonstrate the strong potential of ECT as an enabling technology for intelligent process monitoring and control. However, they also introduce new requirements, particularly regarding domain-specific datasets, computational efficiency, and system robustness under highly variable industrial conditions. In the context of palm oil processing, where oil–water separation efficiency, steam utilization, and environmental sustainability are critical performance indicators, ECT provides a viable pathway for continuous, inline monitoring. Its implementation can contribute to reduced product losses, improved energy efficiency, and enhanced compliance with environmental regulations, particularly in minimizing POME. To achieve full industrial readiness, future research should prioritize

the development of standardized calibration protocols, open-access benchmarking datasets, and large-scale validation under real processing conditions. In addition, closer collaboration among academic researchers, equipment manufacturers, and industry stakeholders will be essential to accelerate technology transfer and practical implementation. Overall, ECT represents a promising and transformative platform for intelligent process diagnostics in agro-industrial systems. Continued advancements in dielectric modeling, sensor design, and real-time AI-assisted reconstruction are expected to further enhance its capability, supporting its transition from a research-oriented technology to a fully deployable solution for next-generation industrial process monitoring. Future research should prioritize field-scale validation, standardized calibration, fouling-resistant sensor design, representative industrial datasets, and techno-economic assessment. Palm oil mill operators are advised to begin with pilot-scale deployment in critical units, such as recovery pipelines, screw press outlets, and clarification tanks. Technology providers should develop modular ECT systems that are compatible with existing plant control and communication systems. Full-scale implementation should proceed only after technical reliability, maintenance requirements, and economic benefits have been demonstrated. This review provides a consolidated reference framework for guiding future ECT implementation in palm oil processing systems. Future commercialization will depend on successful field validation, competitive installation and maintenance costs, and effective integration with existing palm oil mill control systems.

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DECLARATION OF COMPETING INTEREST

None.

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