

Review

Precision Edible Coating Engineering: Deposition Physics, Image Metrology and a Roadmap Toward Digital-Twin-Ready Edible Surface Interfaces

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Highlights

- Edible coatings should be treated as engineered deposited interfaces.
- Processability, atomization and cleanability must accompany film formation.
- Droplet statistics must be linked to coverage, dose and food endpoints.
- CFD/VOF, imaging and AI need validation and uncertainty reporting.
- Scale-up requires CIP, safety, LCA/TEA and reporting standards.

Abstract

Edible coatings are widely studied as food-compatible formulations for reducing moisture loss, oxidation, microbial spoilage, oil uptake, and quality deterioration. Their translation from laboratory formulation to industrial use, however, depends not only on film-forming composition but also on controlled deposition, retained dose, surface coverage, drying history, defect formation, hygienic operation, and reproducible performance on heterogeneous food surfaces. An OpenAlex-supported evidence-map audit (2014–2026) was used to separate direct food-coating validation from adjacent engineering models. This review reframes edible coatings as engineered deposited interfaces and proposes a claim-controlled, evidence-tiered framework linking food-grade biopolymer fluids, processability, atomization, droplet impact, wet-film evolution, dry-film structure, image-based metrology, multiphase modeling, and food-performance endpoints. This review outlines the prerequisites for future digital-twin-ready edible coating workflows by linking functional biopolymer fluids, deposition technologies, droplet physics, intelligent image metrology, Computational Fluid Dynamics (CFD), Volume of Fluid (VOF), uncertainty reporting, food-performance endpoints, safety, Life-Cycle Assessment (LCA), Techno-Economic Analysis (TEA) and patent-aware innovation. Digital twins are treated as a future integration target that depends on validated inputs, standardized reporting, deposition metrology and food-specific model validation. The central argument is that progress in edible coatings requires fewer isolated formulation claims and stronger validated links between deposited-interface properties and food-relevant function. A minimum reporting checklist is proposed to support reproducible comparison of deposition routes, coating structures, and translation potential.



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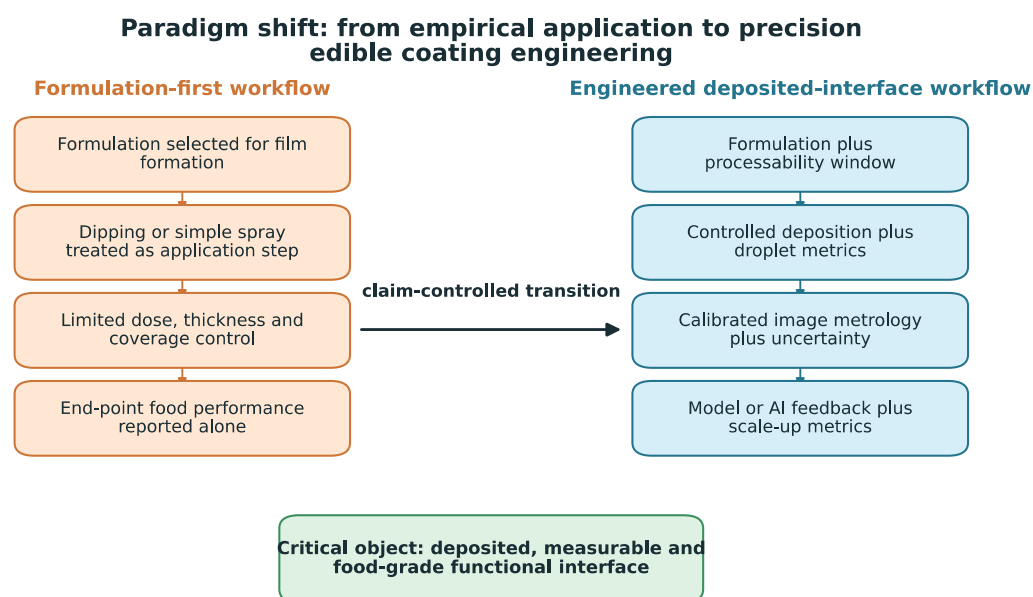
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Keywords: edible coatings; food-grade biopolymers; precision deposition; spray coating; droplet generation; image-based metrology; flow-blurring; rheology; CFD/VOF; digital twin

1. Introduction: Edible Coatings as Engineered Deposited Interfaces

Progress in edible coating research increasingly depends on connecting food-grade formulation design with controlled deposition, quantitative surface metrology, validated modeling, and scalable hygienic processing. Edible films and coatings have been investigated as food-compatible layers for fruit and vegetable preservation [1–9]; antimicrobial and active-packaging functions [10–14]; moisture and gas-barrier control in protein-, polysaccharide- and lipid-based systems [15–19]; safety and translation concerns [20,21]; and oil-uptake reduction in fried foods [22]. However, a formulation that forms a useful film under laboratory conditions is not necessarily pumpable, atomizable, cleanable, reproducible, safe under its intended exposure conditions, or compatible with industrial food-coating equipment [19,21,23–26].

This conceptual transition is summarized in Figure 1.



Fit-for-purpose note: precision routes complement, not replace, validated dipping or conventional spraying.

Figure 1. Paradigm shift from empirical edible coating application to precision deposited-interface engineering. The diagram separates a formulation-first workflow from a claim-controlled engineering workflow in which processability, controlled deposition, image metrology, uncertainty and scale-up metrics are part of the evidence chain. The scheme is conceptual and does not imply universal superiority of AI, microfluidics or precision spray; each food-coating system requires validation.

For the coatings and broad surface-engineering community, the relevant object is not merely a food formulation but a thin functional layer deposited over a complex surface or interface. Viscosity, density, surface tension, solids content, pH, ionic strength, temperature sensitivity, and gelation kinetics affect pumping, atomization, droplet breakup, wetting, coating continuity, drying, and cleaning. These variables determine whether a coating liquid can move from beaker-scale formulation to controlled deposition on irregular, porous, moist, or thermally processed foods [14,15,19,24,27–32].

This review makes four contributions: first, it proposes a droplet-to-film-to-function framework that connects formulation, deposition, coating structure, and food performance.

Second, it applies an open evidence-mapping and patent-aware scouting workflow to identify fragmented convergence among edible coating formulation, deposition technologies, multiphase modeling, and data-driven optimization. Third, it separates direct edible coating evidence from adjacent engineering evidence and roadmap-level proposals. Fourth, it proposes minimum reporting logic for future studies on precision edible coating systems [1,13,15,19,20,30,33–39].

1.1. Engineering Gap in Current Edible Coating Research

Most edible coating studies still follow a formulation-first logic: a polymeric matrix is selected, active ingredients are incorporated, a film or coated food is tested, and preservation performance is reported [9,13–15,20,21,27]. This strategy has generated valuable information on proteins, polysaccharides, lipids, natural extracts, essential oils, nanoparticles, and composite systems [13,15,18,20,27]. Nevertheless, it often underreports the engineering variables that determine whether the coating can be reproduced outside the laboratory. For a coatings audience, the critical object is the deposited interface, not only the liquid formulation [24,40,41]. A more explicit process–structure–function linkage can be established when deposition variables such as retained dose, wet/dry coating thickness, and surface coverage are treated as intermediate state variables between formulation and food-performance endpoints. These descriptors provide a quantitative bridge that allows comparison across coating systems, although the current literature reports remain heterogeneous in measurement protocols and uncertainty reporting [24,42,43].

This engineering gap is especially visible when formulation studies report preservation performance without defining whether the coating liquid remains processable under the shear-rate, extensional-flow, and residence-time conditions imposed by industrial nozzles. Many edible coating fluids are not water-like Newtonian liquids; they may show shear-thinning behavior, viscoelasticity, thixotropy, yield stress, or gelation during pumping and atomization. Therefore, a formulation that is stable during casting or dipping may fail during spraying if the nozzle shear-rate window, extensional viscosity, dynamic surface tension, and clogging tendency are not considered during formulation design. Typical failure modes in coating deposition include non-uniform wet-film thickness on irregular food surfaces, premature drainage on low-viscosity systems, overspray losses exceeding functional dose thresholds, and heterogeneous distribution of active compounds within porous matrices such as fried dough systems. These effects cannot be attributed solely to formulation composition, but rather to coupled formulation–process interactions. Consequently, predictive frameworks such as digital twins become relevant to integrate droplet formation, transport dynamics, and surface response into a unified control structure [44–46].

A precision edible coating workflow must therefore define the relationship among formulation properties, process variables, and measurable surface outcomes. The minimum mechanistic chain should include liquid composition; time-dependent rheology, including yield stress, extensional viscosity and relaxation time when relevant; density; surface tension; solids content; temperature; deposition route; droplet-size distribution; wetting; spreading; coverage; drying; film continuity; and food-performance endpoints. Without this chain, a positive preservation result remains difficult to compare, model, scale, or translate into hygienic equipment [15,19,21,24,27–31,47].

This missing chain also affects economic interpretation. Precision deposition technologies should not be justified only by their theoretical ability to reduce overspray or improve local dose control; they must also be evaluated against equipment cost, nozzle fouling, maintenance frequency, cleaning time, water and chemical use during Cleaning in Place (CIP), and production-time loss during sanitation. In other words, the relevant scale-up question is whether gains in transfer efficiency and coating uniformity outweigh

the operational cost of keeping a precision deposition system hygienic and stable. For this reason, the engineering gap is also a metrology gap: without quantitative evidence of deposited dose, surface coverage, wet-film thickness, dry-film continuity, and local defects, formulation effects cannot be separated from deposition-history effects.

1.2. Why Deposition and Metrology Are Now Central

The distinction between an edible film and an edible coating is not merely semantic. A film is primarily a preformed material specimen, whereas a coating is a process-generated interface whose final structure is created on the food surface. A preformed film can be characterized as a material, whereas a coating is generated in situ; therefore, its function depends on how the liquid is delivered, distributed, retained, dried, and structurally stabilized [13,19]. Dipping, spraying, electrohydrodynamic atomization, ultrasonic deposition, flow-blurring, and robotic deposition produce different histories of shear, droplet breakup, impact, spreading, drainage, and drying. These histories can alter thickness, pinholes, porosity, active-compound distribution, and sensory response even when the starting formulation is identical [24,31,48].

This process dependence also creates a modeling challenge because food surfaces are not ideal smooth walls. Their roughness, porosity, curvature, moisture, cuticular composition, lipid content, temperature, contact-angle hysteresis, and dynamic capillarity define boundary conditions for droplet impact, spreading, penetration, drying, and adhesion. Consequently, Computational Fluid Dynamics (CFD) predictions, including Volume of Fluid (VOF) simulations, require surface-specific validation rather than generic wall assumptions.

Recent studies and reviews have emphasized advanced preparation methods, controlled release, safety, regulation, production scale, circular raw materials, and commercialization barriers in edible films and coatings [9,13,14,18,19,21,23]. However, the deposition layer is still frequently treated as a procedural detail rather than as a mechanistic determinant of coating performance. This creates a methodological weakness: shelf-life or oil-uptake improvement is often reported without sufficient evidence of delivered dose, local coverage, wet-film thickness, droplet distribution, equipment stability, or coating waste [24,49,50].

Image-based metrology should therefore be treated as a validation layer, not merely as visual documentation. Quantitative imaging of coverage, thickness, defect density, wetting patterns, and coating continuity is required to test whether mass-transfer and momentum-transfer models predict the deposited interface rather than only the spray plume or nominal formulation. For porous and irregular foods, uncertainty reporting is essential: thickness, coverage, and defect measurements should include calibration, segmentation error, replicate variability, and confidence intervals before they are used to train AI models or validate digital twins. Techniques can be differentiated based on spatial resolution, measurement accuracy, and robustness to surface heterogeneity. High-resolution microscopy provides superior defect detection but limited scalability, whereas macroscopic imaging enables coverage estimation with lower spatial precision. Intermediate approaches, including structured light and calibrated RGB analysis, offer a trade-off between resolution and industrial applicability on rough and porous food surfaces [51].

Recent authoritative reviews and books show that the edible coating field is mature in terms of biopolymer selection, active-compound incorporation, barrier functionality, preservation endpoints, safety concerns, and food-packaging applications. These reviews have consolidated the roles of polysaccharides, proteins, lipids, composite matrices, antimicrobials, antioxidants, and bioactive carriers in extending food shelf life and reducing quality deterioration. In parallel, the broader functional-coatings literature, including the Wiley volume edited by Arya, Verros and Davim, frames coatings as engineered surface systems

in which coating methods, wetting and dispersing behavior, surface defects, advanced characterization, durability, reproducibility, cost-effectiveness, and machine-learning-assisted development are central to translation. Food-coating-specific Wiley sources further summarize edible biopolymer coatings and practical deposition routes such as dipping, spraying, fluidized-bed coating, and panning. Taken together, the current status of the field can be summarized as follows: edible coating research is well established in formulation chemistry and food-preservation performance, while coating engineering is well developed in surface design, defect control, characterization, and process optimization. However, the intersection between these two bodies of literature remains insufficiently developed for edible food surfaces, especially regarding retained-dose control, quantitative deposition metrology, coating-defect mapping, uncertainty reporting, hygienic validation, and digital-twin readiness. The present review therefore does not claim that edible coatings lack prior reviews; rather, it addresses the underdeveloped engineering link between edible formulation, deposition physics, measurable surface-interface formation, model validation, and industrial translation [1,15,44–46,52–54].

1.3. Aim, Novelty and Claim-Control Strategy

This review positions AI, microfluidic droplet generation, flow-blurring, ultrasonic spraying, and digital-twin workflows as complementary engineering approaches that may expand the capabilities of dipping and conventional spraying when the application context justifies them. Direct edible coating evidence is used for food-performance claims; adjacent engineering evidence is used only to support mechanisms or measurement strategies; and roadmap-level proposals are explicitly identified when a concept is technically plausible but not yet validated at the industrial food scale [22,25,29,30,48,55–58].

Here, claim control means that statements about edible coating performance are grounded in direct food coating evidence, whereas concepts borrowed from adjacent spray engineering, Computational Fluid Dynamics, AI, image analysis, or digital-twin research are used only as mechanistic support or roadmap-level proposals unless food-specific validation is available. This distinction is particularly important for AI-assisted optimization, because model predictions should not be interpreted as industrial maturity unless they are linked to experimentally measured deposited dose, coverage, coating structure, uncertainty, and food-performance endpoints.

Recent reviews have summarized edible films and coatings mainly from formulation, active packaging, sustainability, or application perspectives [9,13,14,18,19]. The gap is defined operationally as the absence of an integrated formulation–deposition–metrology–modeling–translation chain, not as the absence of reviews on edible coatings. Its contribution is a process-engineering and measurement-driven framework that integrates deposition physics, image metrology, multiphase modeling, AI-assisted optimization, digital-twin logic, Life-Cycle Assessment (LCA), Techno-Economic Analysis (TEA), and patent-aware translation without treating these tools as mature industrial solutions by default.

This review has five specific objectives: (a) to classify edible coating systems by engineering function rather than by material family alone; (b) to connect processability, droplet formation, wetting, drying, and food function; (c) to define how image metrology, CFD, VOF modeling, and AI can be used without overstating maturity; (d) to integrate safety, regulation, CIP, LCA, TEA, and patent awareness into the same translation logic; and (e) to propose minimum reporting criteria covering formulation properties, rheological and interfacial inputs, deposition conditions, droplet descriptors, coverage, thickness, defect metrics, image-calibration metadata, uncertainty, food-performance endpoints, cleaning constraints, and scale-up indicators [1,13,15,19,20,25,30,33–36,47,50]. Unlike formulation-centered reviews, it evaluates how processability, deposition route, droplet-to-film mechanisms, metrol-

ogy, modeling, and translation constraints jointly determine coating performance. Concepts from microfluidics, spray engineering, AI, and digital-twin research are treated according to the evidence level: direct edible coating evidence supports food-performance claims, adjacent engineering evidence supports mechanisms or measurement design, and roadmap-level concepts are identified as future opportunities requiring food-specific validation.

Key barriers limiting industrial deployment of digital-twin and closed-loop coating systems include sensor latency under fast spray dynamics, limited robustness of predictive models under highly heterogeneous food surfaces, computational cost for real-time multiphase simulation, and uncertainty propagation from droplet formation to final coating structure. These constraints currently restrict most implementations to pilot-scale or roadmap-level applications [59–61].

To avoid overextending the scope, the revised manuscript focuses the main text on the formulation–deposition–metrology–function chain. Broader enabling dimensions, including Artificial Intelligence (AI), digital twins, Cleaning in Place (CIP), Life-Cycle Assessment (LCA), Techno-Economic Analysis (TEA) and patent awareness, are treated as translation constraints or roadmap-level extensions rather than as parallel central topics. Extended reporting matrices, patent-audit details and roadmap elements are provided in the Supplementary Material so that the main article remains focused on the evidence chain linking coating formulation, deposition history, measurable interface quality and food-performance endpoints.

2. Open Evidence Mapping and Patent-Aware Technological Scan

An open evidence-mapping analysis was conducted to evaluate how edible coating research is positioned relative to precision deposition, atomization, microfluidic carrier generation, image-based metrology, AI, machine learning (ML), CFD, VOF, digital twins, LCA, TEA, food safety, regulation, and industrial scale-up [62]. This article is structured as a critical review rather than as a formal scoping review; the evidence map is used only as a transparency audit trail for the narrative synthesis.

The purpose of this analysis was to map the thematic structure, identify fragmentation across knowledge domains, and determine where formulation-centered edible coating research can be further integrated with process engineering, surface metrology, and digitalization. The procedure is used only for scoping and gap identification; it does not replace source-level claim verification, systematic screening, or formal meta-analysis [33,34,36–39,63].

This procedure should be interpreted as open evidence mapping supporting a critical narrative review. It is not a Scopus or Web of Science Core Collection bibliometric study, a systematic review, a meta-analysis, or a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-based evidence synthesis. Citation metadata recorded during curation correspond to OpenAlex cited_by_count fields and should not be interpreted as Scopus, Web of Science, Journal Citation Reports (JCR), or CiteScore indicators. The patent-aware component is used only to map disclosed technological activity and potential innovation domains; it is not a freedom-to-operate opinion, patentability assessment, regulatory assessment, or proof of technical efficacy [33,34,36–39]. Inclusion criteria were defined at the thematic block level, requiring alignment with at least one of the seven predefined domains (coatings, deposition, microfluidics, imaging, CFD/VOF, AI/ML, or LCA/TEA). Records were excluded when they lacked sufficient metadata for classification, did not relate to edible coating systems or adjacent engineering processes, or could not be reliably mapped to the claim-control framework. This procedure is intended as transparent evidence mapping rather than a systematic PRISMA protocol [64–66].

2.1. Data Sources, Search Blocks and Curation Logic

The scholarly map was constructed from OpenAlex metadata for works published from 2014 to 2026 and organized into seven thematic blocks aligned with the manuscript scope: edible coatings and edible films; deposition and spray application; microfluidics and carrier delivery; AI, ML, and image analysis; CFD, VOF, and multiphase modeling; digital twins and Industry 4.0; and LCA, TEA, and circularity. Digital Object Identifier (DOI) values available only from OpenAlex metadata were treated as metadata fields requiring author-level verification through DOI, Crossref, or publisher records before any record could support a source-level claim [33–39,67,68].

Transparency of Metadata Retrieval and Curation

To support transparency, the metadata and curation procedure is reported as an evidence-mapping approach rather than as a PRISMA evidence synthesis. During curation, the recorded fields included retrieval date, thematic search block, OpenAlex work identifier when available, DOI, normalized DOI, normalized title, publication year, source, document type when available, citation metadata, authorship metadata, evidence code, curation decision, and exclusion or reserve rationale. Deduplication was performed by normalized DOI when present and by normalized title when DOI metadata were absent. Records were retained as manuscript-core references when they directly supported a claim in the text, as background records when they supported mapping or peripheral context, and as reserve-only records when they were relevant but not required for the main argument.

To improve auditability of the evidence-mapping component, the full search strategy, retrieval date, source type, inclusion and exclusion criteria, curation decision, evidence code, DOI-control status, and reserve or exclusion rationale are provided in Supplementary Data S1. The Supplementary File also reports the search blocks used for OpenAlex retrieval, the logic used to deduplicate records by normalized DOI and normalized title, and the criteria used to distinguish manuscript-core references, background records, reserve-only records and excluded records. This information is provided to make the construction of the evidence base reproducible without presenting the article as a PRISMA systematic review, a meta-analysis, or a formal Scopus/Web of Science bibliometric study.

The search strategy was organized into thematic blocks to keep the evidence-mapping logic transparent and prevent the scoping component from becoming a black-box narrative device (Table 1) [37–39].

Table 1. Open evidence-mapping search blocks used for scoping the review. Each block defines the thematic evidence stream and its role in linking edible coating formulation, deposition, metrology, modeling, translation and sustainability.

Block	Scope	Role in the Review
A	Edible coatings and edible films	Core field definition; formulation and material-performance evidence.
B	Deposition and spray application	Links coating performance with application route, dose and transfer efficiency.
C	Microfluidics and carrier delivery	Mechanistic support for controlled droplets, carriers and active delivery.
D	AI, ML and image analysis	Supports data-driven optimization and intelligent metrology when food-relevant.
E	CFD, VOF and multiphase modeling	Methodological bridge for atomization, breakup and deposition physics.
F	Digital twins and Industry 4.0	Roadmap-level support for closed-loop coating engineering.
G	LCA, TEA and circularity	Sustainability, cost and industry-transfer framing.

2.2. Curation Summary and Interpretation Limits

The OpenAlex-based map was used as a scoping layer, not as a formal bibliometric result. The manuscript therefore relies on a curated evidence set rather than on raw metadata-scale indicators. Records were screened by thematic block, DOI and title normalization, source relevance, evidence category, and claim-control function. The resulting curation process recorded whether records were retained for manuscript support, background context, reserve-only status, exclusion, patent-aware technological scouting, or reference-manager control [33–39,64,69,70].

The resulting evidence-mapping and patent-aware claim-control logic is shown in Figure 2.

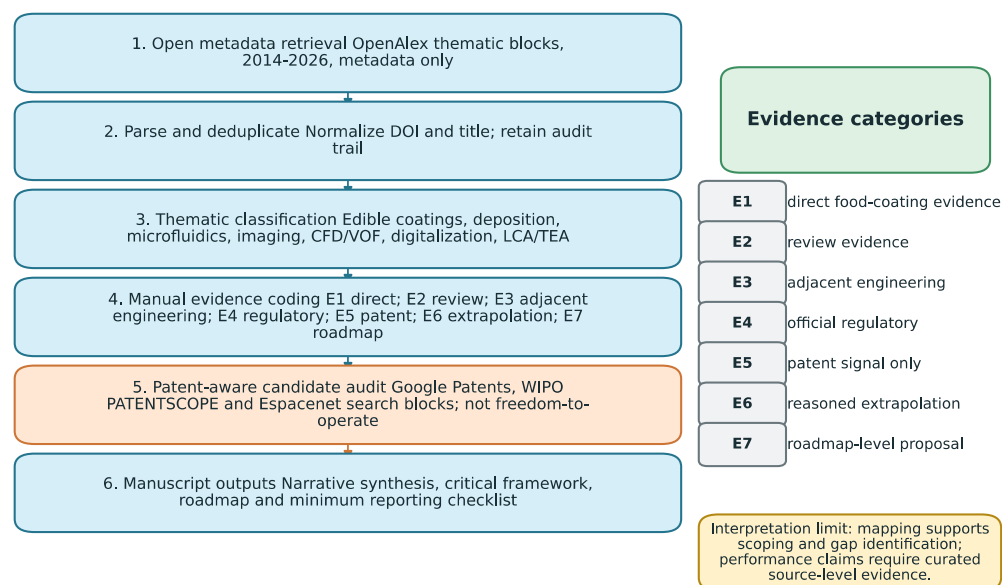


Figure 2. Open evidence-mapping and claim-control workflow used in this review. OpenAlex metadata support thematic scoping and gap identification, whereas curated references are assigned evidence categories before they support manuscript claims. Patent-aware scouting is used only to identify disclosed technological activity and does not constitute a freedom-to-operate, patentability or regulatory assessment.

The curated evidence-mapping descriptors and interpretation limits are summarized in Table 2. They are used to document scoping, curation and claim control, not to report Scopus, Web of Science, Journal Citation Reports (JCR), CiteScore or PRISMA outcomes [33–39].

Table 2. Curated evidence-mapping descriptors and interpretation limits. The descriptors document topic mapping, curation and claim-control decisions only; they are not PRISMA, Scopus, Web of Science, Journal Citation Reports or CiteScore indicators.

Indicator	Value/Interpretation
Review support function	Open evidence mapping and claim-control support for a critical narrative review
Metadata source	OpenAlex scholarly metadata used for scoping; DOI, Crossref or publisher records used for source-level reference control
Publication window	2014–2026
Search-block structure	Seven scholarly search blocks and seven patent-aware search blocks used for scoping and summarized in Tables 1 and 3
Curated candidate audit trail	240 records screened with curation decisions, evidence categories, DOI fields and exclusion/reserve notes

Table 2. *Cont.*

Indicator	Value/Interpretation
Final manuscript references	159 verified/corrected references aligned with the final MDPI citation order
Patent-aware candidates/families	27 candidate signals used only to map disclosed technological activity
Interpretation limit	Scoping and gap identification only; not PRISMA, meta-analysis, formal bibliometric study, regulatory assessment or legal opinion

Table 3. Patent-aware search blocks used to map disclosed technological activity. The blocks identify candidate innovation spaces for edible coating deposition and control, not freedom-to-operate, patentability or regulatory conclusions.

Patent Block	Search Logic	Use in Manuscript
P1	edible coating + spray/atomization/nozzle	Map direct edible coating deposition and atomization activity.
P2	food coating + apparatus/conveyor/nozzle/foodstuff	Map equipment and scalable application systems.
P3	ultrasonic spray + food/foodstuff/edible coating	Support ultrasonic atomization as a disclosed food-related coating route.
P4	electrostatic spraying + food coating/edible coating	Support electrostatic deposition as a disclosed edible coating route.
P5	microfluidic/flow focusing/flow blurring + food encapsulation/coating	Use as adjacent evidence for droplet and carrier engineering.
P6	biopolymer/chitosan/alginate/pectin/whey protein + edible coating	Map composition-oriented edible coating activity.
P7	computer vision/machine learning/artificial intelligence + coating/spraying/deposition/control	Use as roadmap evidence for inspection and closed-loop control.

2.3. Evidence Classification and Claim Control

The evidence-code system used to control claim strength is defined in Table 4 [37–39,71,72].

Table 4. Evidence-classification rules used to control claim strength. The categories separate direct edible coating evidence from reviews, adjacent engineering evidence, official regulatory sources, patent signals, reasoned extrapolations and roadmap-level proposals.

Code	Evidence Category	Permitted Use
E1	Direct edible coating/food coating evidence	Direct claims about formulation, deposition or food performance.
E2	Review evidence	Synthesis, background and gap identification.
E3	Adjacent engineering evidence	Cautious methodological extrapolation for atomization, microfluidics, image analysis, CFD, VOF or AI.
E4	Official regulatory evidence	Food-contact, safety, migration, regulation and standardization.
E5	Patent evidence	Disclosed technological activity only.
E6	Reasoned extrapolation	Cautious wording with explicit transfer limitation.
E7	Roadmap-level proposal	Future direction; not validated industrial practice.

The open evidence map supports the central argument that edible coating research remains strongly anchored in material selection, biopolymer formulation, active compounds, and preservation performance. This emphasis is justified, but it leaves an engineering gap when formulation studies are not connected to the deposition route, droplet physics, coverage, dose control, drying, sanitation, and scale-up. Smaller and more fragmented intersections with image metrology, AI, CFD, VOF, and digital-twin terminology should

therefore be interpreted as evidence of an emerging interdisciplinary frontier, not as evidence of mature industrial implementation [33–39,73].

To connect the proposed reporting framework with the representative literature, Supplementary Data S2 provides a study-level reporting audit. The table evaluates selected edible coating studies and reviews against the minimum information needed for precision edible coating engineering: formulation properties, rheological or interfacial inputs, deposition parameters, droplet descriptors, coverage or thickness measurements, uncertainty reporting, food-performance endpoints, cleaning or sanitation information and scale-up indicators. This synthesis shows that many studies provide strong formulation and food-performance evidence, whereas droplet metrics, deposited-dose control, coverage/thickness metrology, uncertainty, cleanability and scale-up information remain less consistently reported.

2.4. Patent-Aware Technological Scan

A complementary patent-aware technological scan was conducted using documented search blocks in Google Patents, World Intellectual Property Organization (WIPO) PATENTSCOPE, and Espacenet. The scan was organized into seven blocks: edible coating spray; food-coating apparatus; ultrasonic spray for food; electrostatic spray for food; microfluidic encapsulation and droplet generation; biopolymer edible coating compositions; and AI/vision-assisted coating control. The patent component is reported as a candidate-audit and technological-space mapping exercise rather than as an exhaustive automated patent landscape [33,34,36–39]. In response to the need for a more commercialization-oriented interpretation, the patent-aware scan was expanded into a substrate-by-coating-material maturity matrix (Supplementary Data S3). The matrix separates candidate patent signals according to food substrate class, edible coating material class, deposition or monitoring route, digital-twin or data-integration relevance, likely technology-maturity pattern, commercialization signal and evidence limitation. This structure allows the patent-aware component to identify where digital-twin-related coating concepts appear closer to equipment, monitoring or process-control claims, and where they remain only weakly connected to validated edible coating materials and food substrates.

Patent documents are used here as indicators of disclosed technological activity and innovation trends within the field. The identified patent signals highlight technological development related to ultrasonic atomization for food-related coating, electrostatic edible coating, food-coating apparatus, viscous food spray systems, biopolymer edible coating compositions, microfluidic droplet generation, and vision-guided spraying. These signals justify a patent-aware roadmap, but claims about performance, safety, sensory quality, cleaning validation, LCA, or TEA still require peer-reviewed or official evidence [33,34,36–39]. Therefore, the patent-aware scan is used only to identify technological convergence and innovation spaces; it does not establish freedom to operate, commercial readiness, or regulatory acceptability.

The patent-aware technological scan was structured using the seven search blocks listed in Table 3 [37–39].

To deepen the patent-aware interpretation, the revised manuscript adds Supplementary Data S3, which maps candidate patent signals by coated substrate and edible coating material class. The purpose of this matrix is not to establish freedom to operate or to quantify global patent dominance, but to identify where the disclosed technological activity is concentrated and how close each signal appears to commercialization-oriented translation. The matrix distinguishes fruit and vegetable substrates, bakery and fried foods, meat and seafood, dairy or cheese surfaces, and general food-contact or packaging interfaces. It also separates coating material families such as polysaccharides, proteins, lipids or waxes, composite biopolymers, active or antimicrobial systems, nanoemulsion or carrier-based systems,

and smart or indicator coatings. The main trend emerging from the patent-aware matrix is that most disclosed activity remains concentrated around composition, preservation function, spray or apparatus claims, and active food-contact interfaces. Digital-twin-related claims are less frequently linked to a complete edible coating chain that includes a defined food substrate, edible coating material, deposition route, measured coating quality, validated food-performance endpoint, cleaning logic and feedback-control layer. Therefore, digital twins should be interpreted as a roadmap-level innovation domain rather than as a mature commercial category for edible coatings. Stronger technology-maturity signals are associated with conventional food-coating apparatus, spray application and biopolymer or active-coating compositions, whereas lower maturity is observed when digital-twin, Artificial Intelligence (AI), machine vision or closed-loop control language is not connected to food-specific validation. This interpretation supports the central claim-control strategy of the review: patent activity can indicate where companies or inventors are attempting to protect technological space, but it cannot demonstrate technical efficacy, regulatory approval, commercial adoption, hygienic compatibility, sustainability benefit or industrial readiness. For this reason, the patent-aware matrix is used as commercialization-context evidence and not as proof that digital-twin-enabled edible coating systems are already validated at the industrial food scale.

3. Functional Biopolymer Fluids and Processability

A function-based classification is more useful than a material-family classification because the same polymer can serve different roles depending on formulation, deposition route, and food substrate. Whey proteins, polysaccharides, chitosan, alginate, pectin, cellulose derivatives, lipids, and composite systems can act as moisture barriers, oxygen barriers, oil-uptake reduction layers, antimicrobial carriers, antioxidant interfaces, or smart responsive layers [1–7,9–18,20,22,23,27,74–77]. Their relevance to coating engineering depends not only on film-forming ability but also on pumpability, atomization, cleanability, stability, and compatibility with food-grade equipment [24,40,78].

The functional classification used in this review is summarized in Table 5, emphasizing the coating purpose and process constraints rather than the material family alone [24,40,41].

Table 5. Function-based classification of edible coating systems for engineering design. The table links intended coating function with typical materials, critical process variables, deposition concerns and minimum processability evidence.

Function	Typical Materials	Critical Variable	Deposition/Processability Concern	Minimum Processability Report	Selected Supporting References
Moisture-barrier coating	Lipids, waxes, protein–lipid or polysaccharide–lipid composites	Water-vapor transfer, continuity, adhesion	Brittleness, phase separation, poor wetting, wax crystallization, nozzle fouling and sensory residues	Flow curve, dynamic surface tension, emulsion/dispersion stability, filtration step, wetting/coverage map and cleanability	[5,15–18,30]
Oil-uptake reduction coating	Proteins, hydrocolloids, crosslinked systems	Continuity, adhesion, thermal stability	High viscosity, yield stress, thermal gelation, non-uniformity on porous fried surfaces and clogging during spraying	Shear-rate-dependent viscosity, yield stress when relevant, thermal history, D50/D90, retained solids and clogging time	[15,17,22,79]
Oxygen-barrier coating	Proteins and polysaccharides	Pinholes, humidity sensitivity, thickness	Defects, humidity-induced plasticization, thickness variability and poor control of dry-film continuity	Solids content, flow curve, drying conditions, coverage/thickness uncertainty and defect-density analysis	[3,15–18]

Table 5. *Cont.*

Function	Typical Materials	Critical Variable	Deposition/Processability Concern	Minimum Processability Report	Selected Supporting References
Antimicrobial coating	Chitosan, organic acids, essential oils, bacteriocins, phenolic extracts	Surface dose, release, safety	Active-compound loss, pH drift, emulsion instability, matrix crosslinking, microbial risk during recirculation and sensory impact	Active dose, pH/ionic strength, dynamic surface tension, rheology after active addition, microbial stability and recirculation tolerance	[3,7,10,12]
Antioxidant coating	Phenolics, extracts, protein–polyphenol systems	Stability and location of active compound	Phenolic–polymer interactions, viscosity increase, gelation, color change, oxidation during storage and fouling	Rheology before/after extract addition, color stability, oxygen/light exposure history, particle/aggregate size and filtration	[11,13,15,27]
Smart/responsive coating	pH indicators, anthocyanins, responsive matrices, nano-enabled indicators	Sensitivity, reversibility, safety and signal stability	Leaching, photobleaching, optical interference, altered rheology, nozzle clogging and uncertain food-contact safety	Indicator dose, leaching/photostability, signal-to-noise ratio, dynamic surface tension, flow curve after indicator incorporation and safety classification	[80–83]

Retained dose can be quantified through gravimetric balance methods, tracer-based approaches, surface extraction techniques, and image-derived estimations; however, each method introduces distinct uncertainty sources, including evaporation losses, surface heterogeneity, extraction efficiency, and segmentation bias. The absence of standardized protocols currently limits direct comparison across studies and reinforces the need for harmonized reporting frameworks [42,44]. Viscosity, density, surface tension, solids content, pH, ionic strength, temperature sensitivity, gelation, and non-Newtonian behavior form the minimum processability set. Viscosity affects dipping retention, spray atomization, film thickness, and clogging. Density is required to estimate delivered mass, droplet momentum, and multiphase simulation inputs. Surface tension controls breakup, wetting, and spreading. Solids content links liquid dose to dry-film structure. pH and ionic strength affect solubility, charge, aggregation, antimicrobial activity, and gelation. Gelation and crosslinking can strengthen the layer if triggered after deposition, but they can destroy processability if they occur inside lines or nozzles [15,19,21,24,27–32].

A coating formulation should therefore be judged against two linked criteria: its capacity to form a functional film and its capacity to move reproducibly through an industrially hygienic deposition system. Future studies should report formulation properties at the same temperature and under the same shear-relevant conditions used during deposition. Without this information, CFD, VOF, AI, and TEA cannot be built on reliable inputs [15,19,21,24,27–30,47,50].

3.1. Rheological and Interfacial Variables That Should Be Treated as Process Inputs

A key limitation of a purely material-family classification is that it does not treat rheological and interfacial variables as process inputs. Apparent viscosity should be measured over a shear-rate range relevant to pumping, nozzle passage, and atomization rather than reported as a single low-shear value. When available, extensional viscosity, thixotropy, yield stress, and viscoelastic indicators should be reported because these parameters affect filament breakup, satellite droplets, rebound, coating strings, and nozzle fouling. Dynamic surface tension is also relevant because proteins, lipids, emulsifiers, and phenolics may adsorb at interfaces on timescales comparable to droplet formation [18,28,29,31,32,40].

Dynamic surface tension is an important but often underreported input for sprayable edible coatings. Equilibrium surface tension may not represent the interfacial conditions

experienced during atomization, because proteins, emulsifiers, lipids, phenolics, and surfactants may adsorb at newly formed gas–liquid interfaces on timescales comparable to ligament breakup and droplet formation. When available, short-time or time-resolved surface-tension measurements should therefore be reported alongside equilibrium values, especially when CFD/VOF, the Discrete Phase Model (DPM), or surrogate models are used to predict breakup, coalescence, wetting, or early spreading [15,19,21,27,28,30–32,47,84]. The method, interface age, temperature, and concentration should be stated; suitable methods include maximum-bubble-pressure, pendant/drop-volume, or oscillating-drop measurements when compatible with the formulation.

For formulation screening, the practical objective is to identify biopolymer systems capable of forming continuous dry films while maintaining stable and efficient delivery. An extended formulation and processability matrix is provided in Supplementary Table S1. Relevant criteria include phase behavior, controlled droplet formation, hygienic operation, overspray management, and cleaning requirements. This formulation-to-process link is essential because industrial feasibility depends simultaneously on coating chemistry and operational constraints.

For precision edible coating engineering, reporting viscosity at a single shear rate is insufficient. Future studies should provide flow curves over a shear-rate window relevant to storage, pumping, nozzle passage, and atomization, and they should report the fitted rheological model used for engineering interpretation. At minimum, shear-thinning behavior, thixotropy, yield stress, and temperature dependence should be evaluated when hydrocolloids, proteins, emulsions, suspended particles, or active extracts are present. When spray deposition is involved, extensional viscosity should be reported whenever feasible because filament stretching, ligament breakup, string formation, and satellite droplets are controlled not only by shear viscosity but also by the resistance of the formulation to extensional deformation.

3.2. Stability, Filtration and Hygienic Compatibility

Processability also includes stability during storage, pumping, recirculation, and cleaning. Suspended particles, insoluble fiber, protein aggregates, partially hydrated gums, and premature crosslinking can shift a formulation from sprayable to clogging-prone during a single production run. For this reason, edible coating studies should report the filtration step, particle-size limit when relevant, hydration time, aging time, temperature history, and whether the formulation was used once or recirculated. These variables are especially important when translating coatings based on agro-industrial by-products, plant extracts, essential oils, nanoparticles, or mixed protein–polysaccharide systems [9,18,19,21,23,24,85,86].

Hygienic compatibility should be integrated as an intrinsic formulation attribute alongside equipment design. Formulations intended for food-grade coating lines should maintain stable flow behavior, minimize residue accumulation on stainless-steel surfaces, preserve phase homogeneity during operation and shutdown, and support efficient cleaning procedures. Engineering screening should therefore combine film-forming performance with pumpability, nozzle stability, microbial risk, cleaning burden, and residue-removal behavior [15,19,21,24,27–30,50,85].

Cleanability should be treated as a formulation design parameter from the beginning, not as a downstream sanitation issue. Biopolymer-rich liquids may support microbial growth during storage or recirculation, leave adhesive residues on stainless steel, accumulate in dead volumes, form conditioning layers for biofilm attachment, or require aggressive cleaning conditions that compromise sustainability and cost. Therefore, an edible coating formulation should not be considered industrially processable unless its microbial stability,

residue-removal behavior, CIP compatibility, shutdown stability, and recirculation tolerance have been evaluated under realistic time-temperature conditions. Cleanability acceptance criteria should include at least viscosity drift (%), nozzle-pressure increase over time, visible residue score, residue mass or total organic carbon (TOC), microbial-count change, and pass/fail criteria after the selected cleaning cycle.

Recirculation stability is also a techno-economic variable. If overspray, unused coating liquid, or return-line material cannot be recirculated without viscosity drift, phase separation, microbial growth, active-compound loss, particle aggregation, foaming, or nozzle fouling, the apparent material-saving advantage of precision deposition may disappear. Future studies should therefore report whether the formulation was single-use or recirculated, the number and duration of recirculation cycles, temperature history, mechanical shear history, microbial control strategy, and property drift after processing.

In precision edible coating engineering, a formulation is not process-ready simply because it forms a film; it is process-ready only when its rheology, interfacial dynamics, filtration tolerance, recirculation stability, and cleanability remain acceptable under the selected deposition route.

4. Deposition Technologies Beyond Dipping

Deposition technology is the operational link between coating formulation and coating function. Dipping, brushing, conventional spraying, air-assisted spraying, ultrasonic spraying, electrostatic spraying, flow-blurring atomization, microfluidic droplet generation, robotic or conformal deposition, and hybrid strategies should be treated as design choices rather than routine application steps. No route is universally superior. Selection depends on formulation rheology, food geometry, target function, throughput, cleaning burden, cost, regulatory constraints, and measurement strategy [22,29,30,48,55–57,87,88].

A qualitative route-selection logic for edible coating engineering is shown in Figure 3.

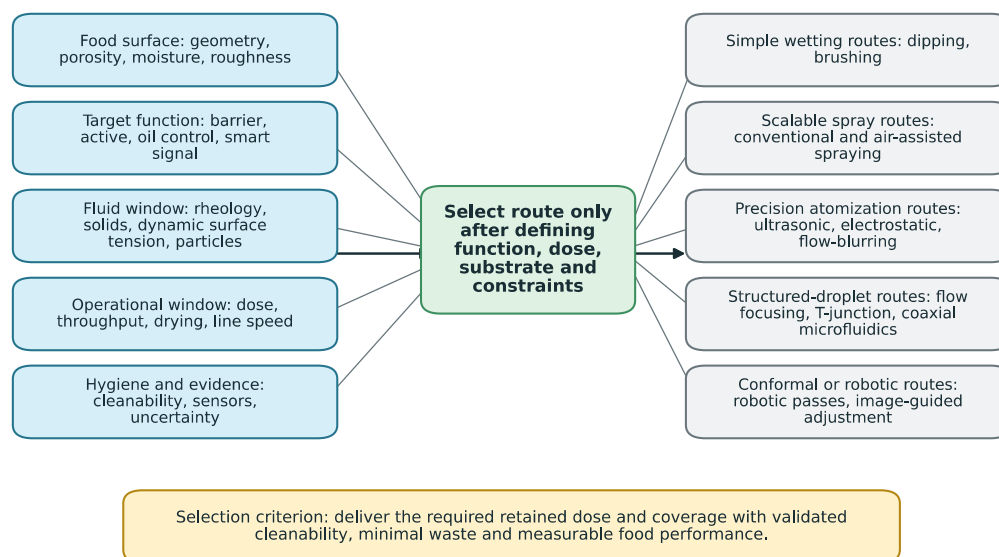


Figure 3. Deposition-route selection logic for edible coating engineering. Route selection starts from food-surface constraints, target function, formulation processability, operating window, hygiene and measurement strategy, and only then considers dipping, conventional spraying, precision atomization, structured-droplet generation or robotic/conformal deposition. The framework is a decision aid, not a technology ranking.

The selection logic in Figure 3 should be interpreted as a decision framework, not as a ranking of intrinsic technology superiority. Technologies such as coaxial microfluidics, flow focusing, flow-blurring, and robotic or conformal deposition remain less validated in

broad edible coating lines than dipping or conventional spraying, but they may be valuable when dose control, carrier structure, localized deposition, or image-guided adjustment is required. Their scalability depends on modular numbering-up, hygienic nozzle design, formulation-specific process windows, and validated metrology.

Dipping remains practical when simplicity, low cost, and complete wetting dominate, but it provides limited control over local dose, drainage, bath hygiene, and coating waste. Conventional and air-assisted spraying are closer to scalable process integration, but they require reporting of nozzle type, flow rate, pressure, working distance, spray angle, line speed, and image-based coverage. Ultrasonic and electrostatic spraying provide higher precision potential and can reduce material use under favorable conditions, but their throughput, cost, formulation window, electrical safety, and food-specific validation must be addressed [29,31,48,55,56,89]. For ultrasonic spraying, the potential advantage is not limited to small droplet size. Because droplet generation and droplet transport can be partially decoupled, ultrasonic systems may produce low-velocity droplets that reduce splashing or rebound and favor gentle spreading on selected irregular or moist food surfaces, provided that wetting, drying, and formulation stability are compatible. This advantage should not be generalized as universal superiority over pneumatic spraying; it should be validated through impact velocity, rebound fraction, transfer efficiency, coverage, and retained dry solids.

Deposition routes should also be compared through mass-transfer efficiency, not only through droplet size or equipment complexity. Relevant engineering variables include delivered wet mass, delivered dry solids, transfer efficiency, coating retention, overspray loss, drainage, rebound, surface coverage, and dry-film uniformity. Without these variables, a coating process may appear effective simply because it delivered more material, whereas an efficient deposition route should maximize functional surface coverage per unit of coating solids consumed.

Microfluidic droplet generation and atomizing spray deposition should be treated as related but distinct engineering routes. Flow focusing, co-flow, T-junction, and step-emulsification devices are primarily useful for producing controlled droplets, emulsions, or active carriers under well-defined microscale flow conditions. By contrast, ultrasonic, pneumatic, electrostatic, and flow-blurring atomizers generate sprays whose droplet distributions depend on nozzle geometry, fluid properties, gas–liquid interaction, operating pressure, flow rate, and environmental conditions [31,32,48,87,88,90–95]. A direct edible coating precedent exists for microfluidic or flow-blurring deposition linked with VOF modeling and fried-food performance [22], but broader validation across viscosities, solids contents, food surfaces, and throughput levels is still required before these routes can be treated as general industrial solutions.

The comparative strengths and limitations of the main deposition routes are summarized in Table 6.

Table 6. Comparative matrix of deposition technologies for precision edible coating engineering. Strengths, best-use cases and limitations should be interpreted relative to formulation rheology, food geometry, target dose, throughput, hygiene and metrology.

Technology	Strength	Best Use	Main Limitation	Selected Supporting References
Dipping	Low cost and complete wetting	Simple geometries and broad contact	Dose control, bath hygiene and waste	[4,15,24,40,89,96,97]
Conventional spray	Industrial compatibility	Fruits, bakery, meat and fried matrices	Overspray, shadowing and variable droplet size	[15,29,55,56]
Ultrasonic spray	Fine droplets and thin layers	Low-flow precision coatings	Throughput, fouling and cost	[29,98]

Table 6. *Cont.*

Technology	Strength	Best Use	Main Limitation	Selected Supporting References
Electrostatic spray	Improved transfer efficiency	Irregular surfaces and active coatings	Conductivity, safety and humidity sensitivity	[56]
Flow-blurring	Strong gas–liquid interaction	Precision atomization of selected fluids	Food-specific validation and solids tolerance	[22,48]
Microfluidic carrier or structured-droplet generation	Droplet precision and carrier design	Carrier preparation, structured droplets, active delivery studies, and low-throughput deposition tests	Numbering-up, cleaning and scale-up	[22,48,87,88,90,91,93,94]
Robotic/conformal deposition	Geometry-adaptive targeting	High-value complex surfaces	Cost, hygiene, speed and robust vision	[26,99–103]

The comparative framework has been extended to explicitly include transfer efficiency, coating uniformity, scalability constraints, hygienic design requirements, and operational cost considerations. This enables a more balanced evaluation of deposition technologies beyond purely droplet-based or geometrical descriptors [12,42,51].

4.1. Deposition Route as a Source of Experimental Bias

The deposition route can act as an experimental confounder. When dipping, spraying, electrostatic deposition, and ultrasonic atomization are compared without controlling delivered solids, wet mass gain, residence time, drying history, and surface coverage, differences attributed to formulation may actually arise from process physics. This is especially relevant for active coatings, where antimicrobial or antioxidant performance depends not only on composition but also on local dose and the release location [13,14,31,32,48,79].

Future comparative studies should therefore normalize and report delivered dry solids per unit food mass or unit surface area whenever possible. They should also distinguish transfer efficiency, coating retention, overspray loss, and final dry coverage. Without these variables, a deposition technology may appear superior simply because it delivered more material, not because it produced a more efficient interface [22,29–32,48,55–57]. They should report mass-balance closure error as applied mass minus retained mass minus overspray/runoff minus evaporative loss, preferably also as a percentage of applied mass.

4.2. Technology Selection Should Be Food-Specific, Not Technology-Driven

The appropriate deposition route should be selected from the food matrix backwards. Smooth fruits, porous fried dough, irregular bakery products, meat surfaces, and cheese rinds impose different requirements for coverage, penetration, drying, safety, and sensory impact [8,9,21]. A technology that produces fine droplets can still fail if those droplets dry before impact, penetrate too deeply into a porous substrate, create visible speckling, or require an excessive number of passes to reach the functional dose. Conversely, a lower-precision but robust method may be preferable when the coating target is bulk wetting rather than micrometric patterning [89,96,97]. Technology selection should also consider monitorability. A precision route is more defensible when its critical outputs can be measured in-line or at-line through intelligent image metrology, including spray stability, droplet descriptors, surface coverage, defect density, rebound, wet-film distribution, and overspray. For this reason, ultrasonic, electrostatic, robotic, or flow-blurring deposition should be justified not only by nominal droplet size, but also by whether the process can be linked to real-time image feedback and corrected through pressure, flow rate, gas–liquid ratio, nozzle distance, trajectory, or line-speed control.

A defensible selection matrix should include at least seven criteria: target function, surface geometry, formulation rheology, desired dose, throughput, cleaning burden, and measurement strategy. Recent work on ultrasonic coating systems demonstrates that deposition variables such as coating time, airflow, liquid temperature, drying conditions, and storage temperature can be optimized against food-quality outcomes, supporting the treatment of coating application as an engineered process rather than as a fixed laboratory step [8,31,48,89,98].

Hygienic design should be treated as a selection criterion for advanced deposition technologies. Ultrasonic nozzles, electrostatic spray heads, microfluidic channels, coaxial atomizers, and robotic end-effectors may introduce narrow passages, dead volumes, charged surfaces, or difficult-to-inspect regions where proteins, polysaccharides, lipids, minerals, or active compounds can accumulate. When allergenic biopolymers such as whey protein, casein, soy protein, or egg-derived ingredients are used, deposition hardware should require validated CIP or clean-out-of-place protocols to prevent cross-contact between product categories. Thus, precision deposition cannot be evaluated only by coating uniformity; it must also be judged by disassembly needs, cleanability, residue detection, microbial control, and allergen-management compatibility.

In precision edible coating engineering, the best deposition technology is not the one that produces the smallest droplets, but the one that delivers the required functional dose with measurable coverage, minimal overspray, acceptable rebound, validated cleanability, and controllable operation under the rheological constraints of the selected food-grade formulation.

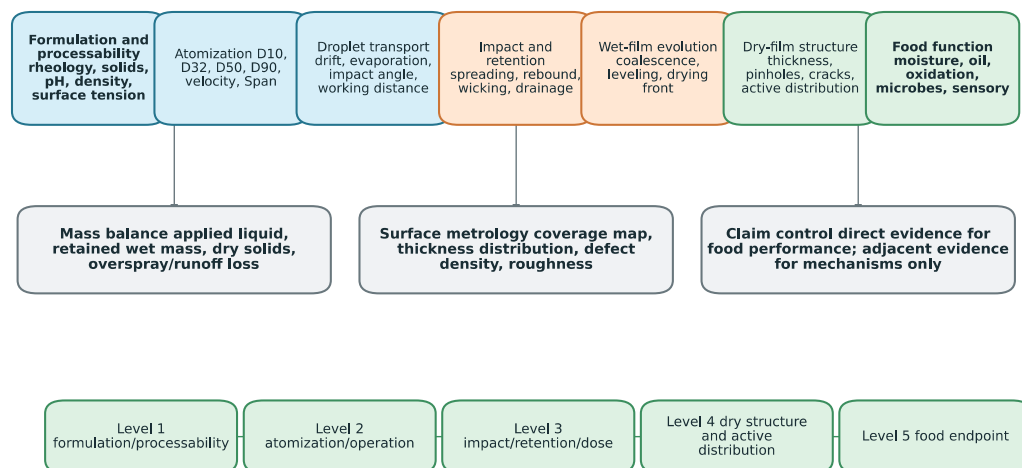
5. Droplet-to-Film-to-Function Physics

After a deposition route has been selected, the critical question is not only whether the coating liquid can be atomized, but also how the delivered droplets become a retained wet layer, a consolidated edible film, and a validated food function. Precision edible coating engineering should therefore be interpreted through a droplet-to-film-to-function chain. This chain links atomization descriptors, droplet transport, impact behavior, wetting, wicking, coalescence, drying, defect formation, dry-film structure, and food-performance endpoints [22,24,29–32,48,55–57,104–106].

This chain is essential for claim control. A formulation may generate an acceptable cast film but fail during spray deposition if it produces unstable ligaments, broad droplet-size distributions, excessive fine drift, clogging, rebound, or poor retention. Conversely, a formulation with modest cast-film properties may perform well when deposited as a controlled thin layer on a specific food surface. The same composition can therefore lead to different outcomes depending on nozzle shear, droplet size, velocity, wetting, drying, and substrate structure.

This systems-level pathway is summarized in Figure 4 and should be read as a claim-control framework, not as evidence that any droplet-size range, atomization route, or process model is universally optimal for all edible coating systems.

Quantitative defect characterization in edible coatings can be described through pore density, crack density, and coating continuity indices. These parameters directly influence barrier performance by governing diffusion pathways for moisture, oxygen, and lipids. However, current studies rarely report standardized defect metrics, limiting direct correlation between deposition conditions and functional barrier outcomes [107,108].



Framework use: connect deposited-interface evidence to food-relevant performance before making precision, modeling or scale-up claims.

Figure 4. Droplet-to-film-to-function framework for precision edible coatings. Liquid properties and process settings determine atomization, transport, impact, retention, wet-film evolution, dry-film structure and food-performance endpoints. Mass balance, calibrated surface metrology and claim-control evidence are required before precision, modeling, AI or scale-up claims are made.

5.1. Atomization Descriptors and Effective Dimensionless Groups

Minimum core droplet descriptors should include D10, D32, D50, D90, coefficient of variation (CV), Span, droplet velocity, working distance, and gas–liquid ratio (GLR) when gas-assisted atomization is used. D10 describes the fine fraction that may drift or evaporate; D32 links droplet volume to surface area; D50 describes the median droplet size; D90 captures the coarse tail that may increase rebound, defects, or non-uniform dose; and CV or Span describes distribution width. These descriptors should be reported with the measurement method, weighting basis, sample size, replicate number, and uncertainty [22,24,29–32,48,55–57,84,104–106].

Classical atomization and coating-flow numbers such as Reynolds number (Re), Weber number (We), Ohnesorge number (Oh), capillary number (Ca), Bond number (Bo), Peclet number (Pe), and, where viscoelastic behavior is relevant, Deborah or Weissenberg numbers can help compare conditions across systems. However, these numbers are meaningful only when the input variables correspond to the process-relevant shear rate, temperature, and composition. For non-Newtonian edible coating fluids, apparent viscosity should be defined at a relevant shear rate, and the constitutive model should be stated [22,24,28,29,31,32,47].

Deposition mode must also be treated as part of the physical interpretation. Flow-blurring and pneumatic atomization have been reported to offer greater tolerance to selected medium-viscosity or higher-solids edible fluids, whereas ultrasonic and electrostatic approaches may be more constrained by the formulation window, conductivity, surface tension, and fouling. Microfluidic droplet generation offers excellent control over droplet size and carrier structure but faces challenges in throughput, numbering-up, and cleanability. Therefore, dimensionless groups and droplet descriptors should be interpreted together with deposition mode and food-surface boundary conditions [22,24,29–32,48,55–57,84,104–106].

5.2. Droplet Impact, Retention and Food-Surface Heterogeneity

After leaving the nozzle, a coating droplet may deposit, spread, recoil, rebound, splash, penetrate, wick into pores, pin at the contact line, or coalesce with neighboring droplets. The drop-impact literature shows that these regimes depend on inertia, viscosity, surface tension, surface roughness, wettability, air cushioning, and substrate compliance [104–106]. For edible coatings, these mechanisms must be interpreted cautiously because food surfaces

may be moist, porous, oily, rough, heterogeneous, deformable, and thermally changing. Thus, a droplet-size statistic without impact velocity, substrate description, wetting behavior, and retained-mass evidence is insufficient to support a precision-deposition claim without impact-velocity distribution or mean $\pm$ SD velocity at the food surface.

This point is central for food-specific technology selection. A smooth fruit cuticle, porous fried crust, moist meat surface, cheese rind, and bakery surface can require different droplet-size and impact-energy windows. Droplets that improve coverage on one substrate may splash, rebound, wick too deeply, or create sensory defects on another. Consequently, droplet descriptors must be linked to the substrate, coating structure, and food endpoint [22,24,29–32,55–57,104–106].

Direct edible coating studies support this system-specific interpretation. Spray-coating optimization has been shown to affect active edible coating performance on plantain epicarp, electrostatic and conventional spraying have been compared for alginate-based antimicrobial coatings on strawberries, and microfluidic edible coating work has connected atomization, VOF modeling, image analysis, and fried-food performance [22,55,56]. These examples should not be generalized as proof that one deposition technology is universally superior; rather, they show that food performance depends on the coupled formulation–deposition–surface system.

For porous or thermally processed foods, impact and retention must also be distinguished from penetration. A coating may appear uniformly deposited in a top-view image while part of the liquid has wicked into pores or cracks, reducing the concentration of active material at the external surface. This is especially relevant when the coating is intended to act as a moisture barrier, antimicrobial layer, antioxidant layer, or oil-uptake reduction interface. In these cases, surface coverage should be complemented by retained wet mass, dry solids per unit area or food mass, cross-sectional imaging when feasible, and functional validation against the target endpoint [13,14,22,24,30,55–57,79,96,97].

5.3. Wetting, Wicking and Delivered Dose

A low apparent contact angle may favor rapid spreading and visually continuous coverage, but it does not automatically imply better adhesion, stronger barrier performance, higher active-compound availability, or improved preservation. On porous or rough foods, extensive wetting can increase capillary penetration, dilute the surface-active fraction, reduce local film thickness, alter texture, or accelerate non-uniform drying. Conversely, a higher contact angle may reduce spreading but improve localization of a functional layer when surface action is required. An apparent and time-resolved contact angle should therefore be reported with the surface used, time after deposition, temperature, roughness or model-surface rationale, and, when possible, advancing and receding contact angles or contact-angle hysteresis rather than a single static value [24,31,32,104–106].

Delivered dose should be separated from apparent coverage. For industrially relevant comparisons, studies should report at least applied liquid mass, retained wet mass, estimated dry solids per unit food mass or surface area, transfer efficiency, overspray loss, drying conditions, and final film thickness or thickness distribution. Without these measurements, a deposition route may appear superior simply because it delivered more solids, rather than because it generated a more efficient interface. This distinction is especially important for antimicrobial, antioxidant, and oil-barrier coatings, where local dose, active-compound location, and spatial distribution can dominate the observed endpoint [13,14,22,24,30,55–57,79,84,96,97,104–106,109–111].

For irregular foods, dose reporting should include transparent surface-area and mass-balance logic. Gravimetric measurement can estimate applied and retained wet mass; solids content can convert retained wet mass to nominal dry solids; calibrated image analysis, cross-

sections, profilometry, or thickness mapping can help determine whether this nominal dose is actually located at the intended surface. When a food surface has cavities, pores, cracks, or strong curvature, the uncertainty of area estimation and segmentation should be stated because both can bias transfer-efficiency and coverage claims [22,24,26,84,100–106,109–111].

5.4. Drying, Coalescence and Defect Formation

The final edible coating is not a direct geometric copy of the incoming droplet distribution. It is formed through wet-film coalescence, solvent evaporation, drainage, polymer concentration, gelation, crystallization, lipid structuring, emulsion destabilization, protein or polysaccharide network formation, and possible phase separation. These transformations can generate pinholes, cracks, coffee-ring-like deposits, edge thickening, active-compound gradients, brittle regions, or non-uniform optical appearance. Drying history should therefore be treated as a mechanistic variable rather than as a routine post-treatment step [19,24,41,109–111].

Adjacent drying and coating-science evidence is useful for interpreting these risks, but it must be transferred cautiously to edible biopolymer systems. Coffee-ring formation illustrates how evaporation and contact-line pinning can concentrate dispersed material at droplet edges; the latex-film literature shows how drying fronts, particle packing, and coalescence can control final film morphology [109–111]. Edible coatings are chemically different from latex systems, yet the general principle is transferable: the functional dry layer depends on the evaporation rate, solids redistribution, capillary flows, film consolidation, and mechanical stress development. For edible coatings, this logic must be validated through wet-to-dry mass conversion, drying time, thickness dispersion, optical or microscopic defect mapping, and replicate stability [24,41,109–111].

Excessive evaporation before impact can reduce retention and produce powdery or weakly attached deposits; prolonged residence time before stabilization can increase drainage, tackiness, or process-hygiene concerns; rapid surface solidification can trap water or create internal stresses; and non-uniform drying can alter texture, color, gloss, and sensory perception. Edible-film studies show that drying temperature and formulation composition can change thickness, solubility, water-vapor permeability, mechanical response, microstructure, and antioxidant behavior, supporting the treatment of drying conditions as experimental variables that must be reported rather than as background details [13,19,24,41,109–111]. A precision coating study should therefore report temperature, relative humidity, airflow, residence time, surface temperature when relevant, and whether drying occurred before, during, or after food processing [13,14,19,24,30,57,79,109–111].

5.5. Linking Film Structure with Food Function

A lower D50 does not automatically improve coating performance; it may increase coverage while reducing local film thickness or retained mass. A lower contact angle does not automatically improve function; it may improve spreading while increasing penetration into porous foods. A more uniform visual coating does not automatically improve shelf life; it must be connected to barrier continuity, active-compound location, microbial response, oxidation, oil uptake, moisture loss, texture, color, gloss, or sensory acceptance. The relevant target is a validated droplet distribution and deposition pattern that matches the food matrix, coating function, and process window [22,24,29,30,55–57,84,96,97,104–106,109–111].

A proposed coating-formation validation hierarchy can reduce overclaiming. Level 1 reports formulation and rheology only. Level 2 adds droplet-size statistics and operating variables. Level 3 adds impact, retention, coverage, delivered dose, and wet-film behavior. Level 4 adds dry-film thickness, defect density, active-compound distribution, and drying uncertainty; in Table 7, this level is separated into structural and active-distribution

sublayers to avoid merging distinct validation tasks. Level 5 links these measurements to food-performance endpoints under replicated and food-relevant conditions. This hierarchy is not a formal standard; it is a claim-control reporting matrix proposed by this review to make precision edible coating claims more reproducible and less dependent on qualitative surface appearance. The required depth should match the strength of the claim being made. Table 8 summarizes the hierarchy for future studies that claim precision deposition, optimization, modeling, AI support, or industrial translation.

Table 7. Formula-level interpretation of droplet descriptors, dimensionless groups and deposition-mode constraints for non-Newtonian edible coating fluids. Descriptors are engineering aids, not universal thresholds; their validity depends on the selected fluid model, measurement window, route and food surface.

Engineering Element	Suggested Definition or Descriptor	Main Limitation in Edible Coatings	Minimum Reporting or Validation
D10, D32, D50, D90, CV and Span	Distribution descriptors for fine fraction, surface-area scale, median scale, coarse tail and distribution width.	Distribution values can look favorable while transfer efficiency, velocity, drying, retention or coverage remain poor.	Report method, weighting basis, sample size, replicate runs, uncertainty, droplet velocity, working distance and environmental conditions.
Re _{app}	$Re_{app} = \rho U D / \mu_{app}$; inertial-to-viscous ratio using apparent viscosity.	Low-shear viscosity can misrepresent nozzle passage, ligament breakup or spreading in shear-thinning fluids.	Report shear-rate window, rheological model, temperature, solids content, hydration/aging time and the viscosity value used.
We _{dyn}	$We_{dyn} = \rho U^2 D / \sigma_{dyn}$; inertial-to-interfacial ratio during breakup or impact.	Equilibrium surface tension can be misleading when proteins, surfactants, lipids or phenolics adsorb during atomization.	Use dynamic or short-time surface tension when available; state measurement time scale and interface age.
Oh _{app}	$Oh_{app} = \mu_{app} / \sqrt{(\rho \sigma D)}$; combines viscous, inertial and interfacial effects.	A single Newtonian value can hide viscoelastic damping, gelation, particle burden or solids-induced breakup changes.	Report apparent viscosity, surface-tension basis, characteristic diameter, density and uncertainty.
Ca	$Ca = \mu_{app} U / \sigma$; viscous-to-interfacial stress during spreading, leveling or drainage.	May fail when the wet layer develops yield stress, gelation, strong thixotropy or rapid solvent loss.	Report spreading time, substrate, temperature, liquid age and whether the liquid is Newtonian or non-Newtonian.
Bo	$Bo = \Delta \rho g D^2 / \sigma$; gravity-to-capillarity ratio.	Small droplets may be capillary-dominated, whereas larger retained drops can drain or run off on curved or inclined foods.	Report orientation, curvature, residence time before drying and whether runoff/drainage was measured.
Pe	$Pe = UL / \alpha$ or $Pe_m = UL / D_m$; convective-to-diffusive transport.	Thermal or mass-transfer Pe values depend on the chosen length scale and diffusivity; misuse can obscure drying gradients.	Define whether Pe refers to heat, water, solvent or active-compound transport; report L, U, diffusivity and drying conditions.
De	$De = \lambda / t_{process}$; material relaxation time relative to process time.	Often omitted although elastic filament persistence, recoil or stringing can influence atomization and impact.	Report relaxation-time method when measurable; otherwise state that viscoelastic effects were not quantified.
Contact angle and hysteresis	Apparent, advancing and receding wetting descriptors.	Static contact angle alone does not capture roughness, porosity, absorption, time-dependent wetting or contact-line pinning.	Report substrate, droplet volume, time after deposition, temperature, humidity and model-surface rationale.
Transfer efficiency and retained mass	Applied liquid mass, retained wet mass, dry solids per area or food mass and overspray/runoff loss.	Coverage images can overestimate functional dose when material drifts, drains, penetrates or dries before impact.	Report mass-balance closure, surface-area estimation, retained wet mass, dry-solids conversion and uncertainty.

Table 7. Cont.

Engineering Element	Suggested Definition or Descriptor	Main Limitation in Edible Coatings	Minimum Reporting or Validation
Route-specific constraints	Ultrasonic, pneumatic/flow-blurring, conventional or air-assisted spray restrictions.	Each route changes the relationship between rheology, breakup, droplet statistics, fouling and throughput.	Report nozzle type, frequency or pressures, liquid/gas flow rates, GLR, pressure stability, clogging/fouling time and sequential-run repeatability.
Drying and defect descriptors	Wet-to-dry conversion, thickness dispersion, pinholes, cracks, edge thickening and active distribution.	A uniform wet layer can dry into a cracked, edge-thickened or compositionally heterogeneous dry film.	Report drying temperature, relative humidity, airflow, residence time, surface temperature, imaging method, defect definition and replicate stability.
Note for Table 7: ρ is liquid density; U is the characteristic droplet or flow velocity; D is the characteristic droplet, nozzle or film length scale, as appropriate; μ_{app} is the process-relevant apparent viscosity; σ and σ_{dyn} denote equilibrium and dynamic surface tension, respectively; $\Delta\rho$ is the density difference; g is gravitational acceleration; α is thermal diffusivity; D_m is molecular or effective mass diffusivity; λ is material relaxation time; and $t_{process}$ is the relevant process time. The selected length scale, property basis and measurement time scale should be stated because alternative choices can change numerical interpretation.			

Table 8. Tiered reporting matrix for precision edible coating studies. Core tiers support reproducibility; advanced tiers are required when the manuscript claims precision deposition, modeling, AI optimization, digital-twin readiness or industrial translation.

Validation Tier	Metric or Evidence Layer	Role in Edible Coating Engineering	Recommended Reporting Logic
Level 1: formulation/processability	Composition, solids, density, pH, rheology, surface tension and stability.	Defines whether the liquid can plausibly be pumped, atomized, deposited and dried.	Report temperature, hydration/aging time, rheological model, shear-rate window, surface-tension basis and filtration/particle status.
Level 2: atomization and operating variables	D10, D32, D50, D90, CV, Span, velocity, nozzle geometry, flow rate, pressure, GLR, working distance, angle and environment.	Connects droplet formation and transport to the process window.	Report equipment geometry, method, sample size, weighting basis, confidence interval, pressure/flow stability, temperature, relative humidity, airflow and replicate runs.
Level 3: impact, wet film and delivered dose	Retention, rebound/splash, spreading, wicking, drainage, coverage map, dry solids per unit area or food mass, transfer efficiency and overspray/runoff loss.	Determines how much coating actually remains and how it is distributed before drying.	Report retained wet mass, drainage time, solids conversion, surface-area estimation method, image calibration, segmentation method, mass-balance closure and uncertainty. Report mass-balance closure error (%) and define whether evaporative loss was measured or estimated.
Level 4a: dry structure	Thickness, thickness dispersion, pinholes, cracks, edge thickening, optical defects and film continuity.	Connects deposition pattern with barrier, release and sensory function.	Use cross-section, profilometry, mass-balance estimate or validated imaging; report defect definition, analysis area, drying conditions and replicate variability.
Level 4b: active distribution and drying uncertainty	Active-compound location, drying time, temperature, humidity, airflow, surface temperature and wet-to-dry conversion.	Controls antimicrobial, antioxidant, barrier and sensory outcomes.	Report whether drying is in-line or post-process, whether active compounds are surface-localized or embedded, and whether drying alters release or activity.
Level 5: food endpoint	Oil uptake, moisture loss, oxidation, microbial counts, respiration, texture, color, gloss, sensory acceptance or shelf life.	Links film structure to real food performance.	Report food matrix, storage/processing conditions, endpoint method, controls, statistics, food-relevant replication and failure cases.
Claim-control layer	Evidence category and validation depth.	Prevents overclaiming from adjacent engineering evidence or small laboratory datasets.	Use direct edible coating evidence for food-performance claims; use adjacent evidence only for mechanisms, measurement selection or validation requirements.

Taken together, the droplet-to-film-to-function framework shifts edible coating interpretation from formulation performance alone to coating-formation evidence. It also

defines the experimental observables that should serve as validation targets for the multi-phase modeling, surrogate-modeling, and digital-twin layer discussed in Section 6. In this structure, Section 5 evaluates the coating-formation chain, whereas Section 6 evaluates the model-validation chain. Maintaining that distinction prevents modeling terminology from being used without measured coating outcomes.

5.6. Digital-Twin Limitations and Online Measurement Uncertainty

Digital-twin implementations in edible coating processes remain constrained by data availability, measurement uncertainty, and limited experimental validation under industrial conditions. High-frequency datasets linking droplet formation, surface coverage, and final food performance are rarely available, limiting model generalization.

Online measurement systems introduce systematic errors including lighting variability, camera calibration drift, motion blur, occlusion of droplets, segmentation bias in image analysis, and refractive distortions on moist food surfaces. These errors propagate into derived metrics such as droplet size distribution, coverage fraction, and coating thickness.

From a modeling perspective, current AI-based approaches rely on supervised learning (CNN-based segmentation, U-Net architectures, object detection models such as YOLO) and hybrid physics-informed methods (PINNs, Gaussian process surrogates, reduced-order CFD models). However, their reliability depends strongly on dataset representativeness and calibration quality, limiting direct industrial deployment without robust uncertainty quantification frameworks [46,61,112].

6. Multiphase Modeling, Surrogate Models and Digital-Twin Architecture

In this review, the digital-twin architecture is presented as a roadmap-level target rather than as an already validated production framework. At the current evidence level, most edible coating systems should be described as candidates for bounded surrogate modeling or decision-support tools unless formulation inputs, deposition metrology, uncertainty updating and food-specific validation are available.

The roadmap-level digital-twin architecture proposed for precision edible coating engineering is shown in Figure 5.

CFD/VOF, Discrete Phase Model (DPM), and reduced-order surrogate models can support edible coating engineering when used as validated tools rather than as decorative terminology; Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), level-set, front-tracking, lattice Boltzmann methods, and physics-informed neural networks (PINNs) should be retained only when their specific validation role is stated. Their value lies in connecting input fluid properties and equipment geometry with measurable coating outcomes such as droplet-size distribution, coverage, wetting, thickness, defects, and food performance [28,29,47,92,113–123].

The VOF method is especially relevant for gas–liquid interfaces because it can represent ligament formation, interfacial deformation, and droplet detachment. Direct edible coating evidence remains limited but important: a coatings study integrating microfluidic spray, VOF modeling, physicochemical characterization, image analysis, and fried-food performance provides a methodological precedent [22]. Still, most spray and multiphase modeling evidence comes from adjacent fields; therefore, transfer to food-grade biopolymer coatings requires validation, mesh and time-step sensitivity, boundary-condition transparency, and uncertainty reporting [47,113,114].

For most edible coating systems, digital twins and closed-loop optimization should be presented as roadmap-level architectures rather than mature industrial tools [124–128]. A credible digital-twin workflow requires four elements: a validated material and process model, calibrated measurements of coating outputs, an updating mechanism that compares

predictions with measured data, and a decision layer that adjusts controllable variables within safety, hygiene, and regulatory constraints. Without measured feedback and constrained actuation, the term digital twin should be replaced by simulation model, surrogate model, or conceptual workflow.

Roadmap-level digital-twin architecture for edible-coating deposition

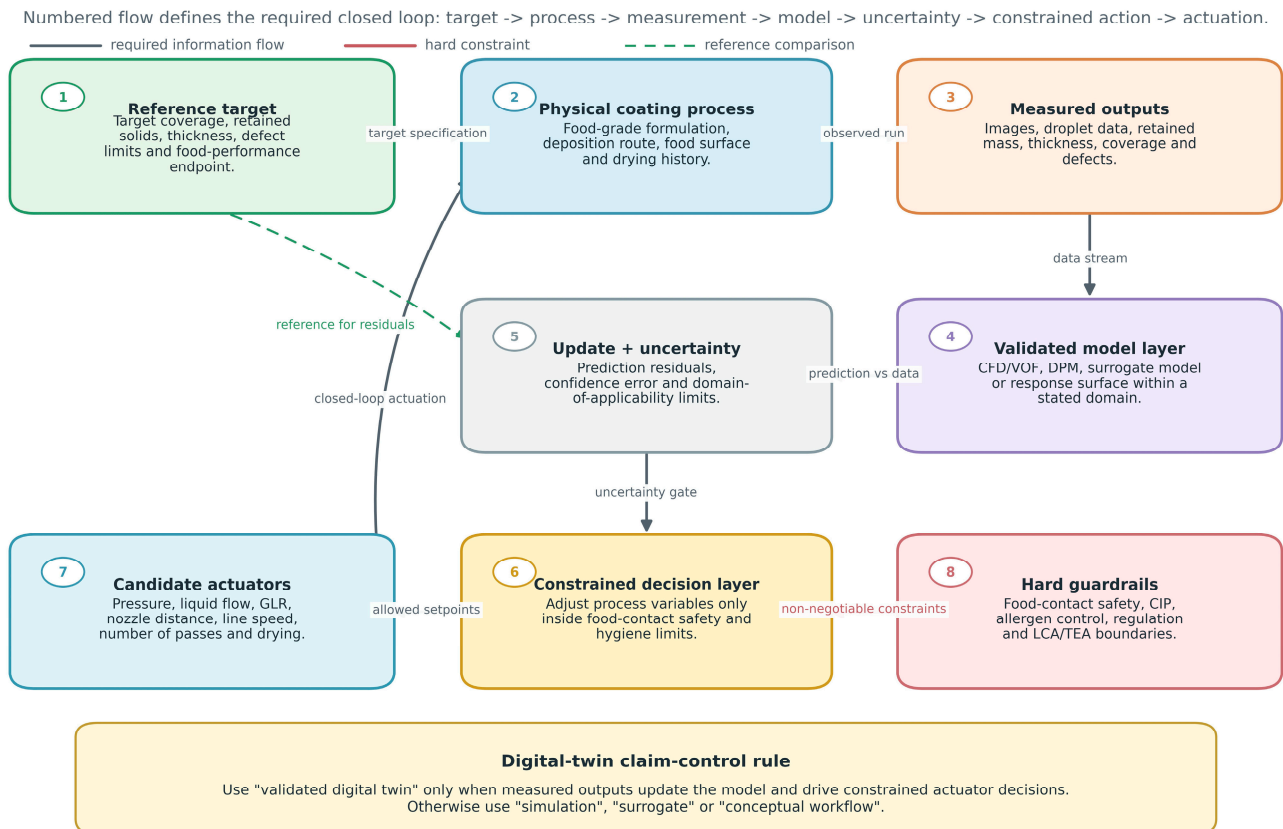


Figure 5. A defensible loop requires a reference target, a physical coating process, measured outputs, a validated model layer, uncertainty updating and constrained actuator decisions within food-contact safety, hygiene and regulatory limits. Without measured outputs and experimental updating, the workflow should be described as a simulation or surrogate rather than a validated digital twin.

6.1. Validation Hierarchy for CFD and VOF

For review-level claim control, modeling evidence should be ranked by validation depth. The lowest level is a conceptual simulation with qualitative agreement only. A stronger level reports geometry, mesh, time step, boundary conditions, and fluid properties. A still stronger level includes mesh and time-step independence, experimental validation against droplet size or ligament behavior, and uncertainty reporting. The strongest level links simulated atomization or deposition variables with food-relevant outcomes such as coverage, thickness, oil uptake, moisture loss, or shelf-life extension [22,28,47,113–115,120]. Numerical verification should report Courant-number control, residual or convergence criteria, mesh-refinement and time-step-refinement results, and the relative change or grid-convergence index (GCI) for target outputs such as D32, D50, deposition flux, or coverage.

For edible biopolymer fluids, CFD validation should also include a rheological closure appropriate to the formulation. Water-like Newtonian assumptions are insufficient for pectin, alginate, zein, chitosan, whey-protein, starch, or mixed hydrocolloid systems when shear-thinning, viscoelasticity, thixotropy, or yield stress are present. Shear-thinning fluids may be represented through power-law, Cross, or Carreau–Yasuda models, whereas paste-like or yield-stress systems may require Bingham or Herschel–Bulkley formulations. The

selected constitutive law should be fitted at the temperature, solids content, and shear-rate range relevant to nozzle passage and atomization. Rotational rheometry is useful for low-to-moderate shear screening, but spray simulations should not be considered fully validated if they rely only on low-shear data; capillary rheometry at high shear rates and, when feasible, extensional rheology should be used to characterize nozzle flow, ligament stretching, and satellite-droplet formation.

This hierarchy is essential because most of the CFD and VOF atomization literature is adjacent engineering evidence rather than direct edible coating evidence. It can support mechanism, model design, and parameter selection, but it cannot by itself establish food-grade feasibility. The manuscript should therefore use cautious language when extrapolating from agricultural spray, inhaler spray, emulsion atomization, or non-food multiphase systems [22,29,30,47,55–57,113,114].

6.2. Minimum Architecture for a Food-Grade Coating Digital Twin

A practical digital twin for edible coating engineering should contain at least four coupled layers. The material layer includes formulation, rheology, dynamic surface tension, density, solids, pH, and stability. The process layer includes nozzle geometry, flow rate, pressure, gas–liquid ratio, working distance, line speed, temperature, and drying. The measurement layer includes droplet statistics, image-based coverage, wet or dry thickness, defects, and uncertainty. The decision layer links these measurements to constrained process adjustments and food-performance endpoints.

Operationally, this conceptual architecture can be implemented as a three-layer closed-loop control system. The first layer is the physical-input layer, including fluid density, dynamic surface tension, apparent viscosity or fitted rheological model, solids content, nozzle pressure, flow rate, gas–liquid ratio, working distance, and line speed. The second layer is the inference layer, where high-fidelity CFD/VOF-DPM simulations are reduced into surrogate models, response surfaces, or physics-informed neural networks (PINNs) able to estimate droplet descriptors, deposition flux, coverage probability, or wet-film thickness within the validated operating domain. The third layer is the sensing-and-control layer, where high-speed imaging near the nozzle and line-scan, red–green–blue (RGB), multispectral, or hyperspectral imaging over the food surface quantify D50, D32, Span, coverage, defect density, or coating uniformity; these measurements are then used to adjust pump pressure, liquid flow, gas–liquid ratio, nozzle distance, or line speed. Under this definition, a coating digital twin becomes credible only when it updates model predictions with measured data and converts them into constrained control actions.

This architecture prevents the term digital twin from being used as a generic visualization label. Unless a model is updated by experimental data, checked against measured coating outcomes, and connected to decisions, it should be described as a simulation model, surrogate model, or conceptual workflow rather than as a validated digital twin [22,25,28,58,61,115,120,124–127].

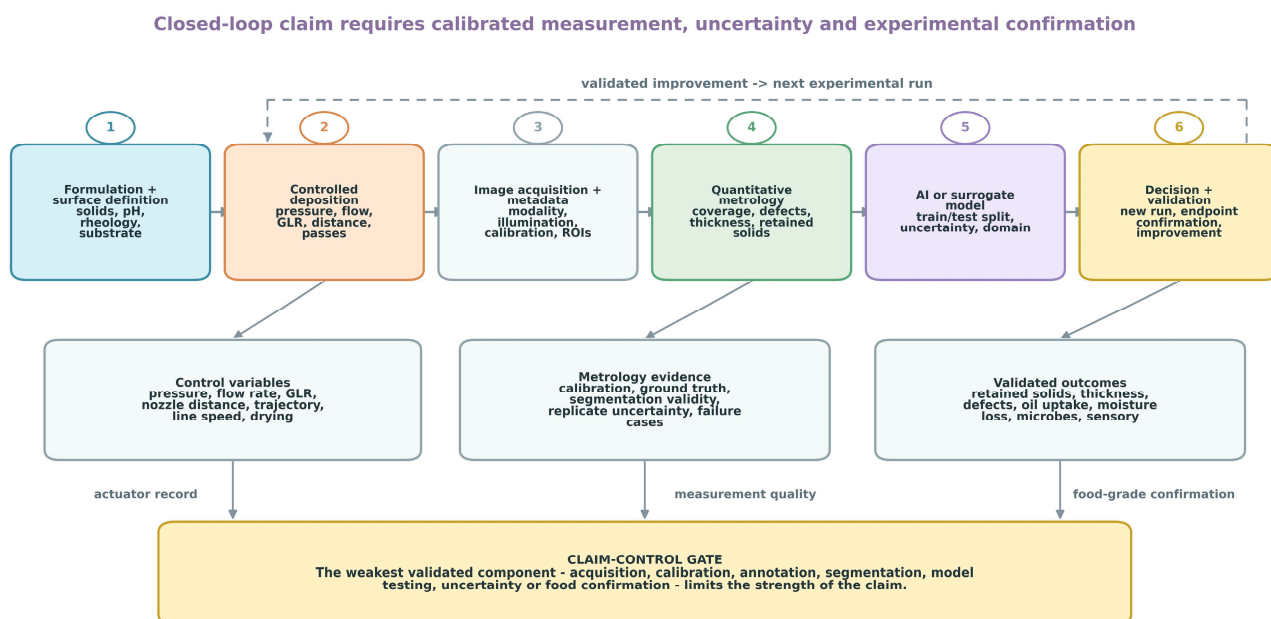
7. Intelligent Image Metrology and AI-Assisted Optimization

Intelligent image metrology is the measurement layer that converts deposited edible coating interfaces into quantitative evidence for model calibration, process optimization, and claim control. Within the engineering framework of this review, image analysis should not be treated as visual documentation added after the experiment, but as a planned measurement system that links formulation properties, deposition conditions, droplet-to-film formation, dry-film structure, and food-performance endpoints. This distinction is critical because a coating that appears visually uniform may still differ in retained dry

solids, wet-film thickness, pinhole density, local penetration, active-compound distribution, drying defects, barrier continuity, and sensory acceptability [9,26,74,75,80,99–103,129–138].

For precision edible coating engineering, the minimum function of image metrology is not to produce representative images, but to generate calibrated descriptors of the coating interface. Relevant descriptors include droplet statistics, surface coverage, retained wet area, dry-film continuity, thickness distribution, local roughness, defect density, color or gloss response, drying kinetics, and, when chemically feasible, the spatial distribution of active or barrier-forming solids. These descriptors should be connected to independent mass-balance, rheological, interfacial, drying, structural, or food-performance evidence. Without this link, image-based claims remain qualitative, and AI-assisted optimization may reproduce laboratory-specific visual artifacts rather than generalizable coating behavior [135,139–141].

This section defines the measurement-to-decision layer required for AI-ready edible coating studies. It separates imaging-modality selection, acquisition metadata, calibration, annotation, segmentation validity, uncertainty reporting, model training, optimization, data documentation, and experimental confirmation. This separation prevents image analysis, machine learning, and digital-twin terminology from being used as unvalidated labels. The strength of a claim should not exceed the weakest validated component of the chain: acquisition, calibration, annotation, segmentation, model training, uncertainty analysis, domain-of-applicability definition, or food-grade experimental confirmation. The resulting measurement-to-decision sequence is summarized in Figure 6.



Minimum defensible AI-ready record: measurand, acquisition metadata, calibration, segmentation validation, uncertainty, independent test and food-endpoint confirmation.

Prediction alone is not a closed-loop metrology claim unless measured outputs and a confirmed decision rule are reported.

Figure 6. Measurement-to-decision pipeline for AI-ready edible coating metrology. Image acquisition becomes actionable only when the measurand, metadata, calibration, segmentation validity, uncertainty, model testing, decision rule and experimental confirmation are reported. Suggested control variables include pressure, liquid flow rate, gas–liquid ratio (GLR), nozzle distance, trajectory, line speed and drying conditions.

7.1. Measurement Targets: From Surface Appearance to Quantitative Coating Descriptors

The first requirement for intelligent image metrology is to define the measurand before image acquisition. In edible coating studies, the measurand may be droplet size, wet surface coverage, retained coating area, dry-film continuity, local thickness, pinholes,

cracks, edge thickening, color change, gloss, active-compound localization, or drying-front progression. Each measurand requires a different imaging strategy, spatial resolution, calibration procedure, and validation metric. A single photograph cannot support all of these claims [135,137,139–142].

Droplet descriptors require in-flight imaging, high-speed imaging, shadowgraphy, laser diffraction, or validated image-based droplet analysis, together with working distance, illumination, exposure time, thresholding criteria, sampling volume, and sample size. Surface coverage requires spatial calibration, defined regions of interest (ROIs), blank-surface controls, and segmentation validation. Thickness and topography require profilometry, optical coherence tomography, confocal microscopy, cross-sectional microscopy, calibrated mass-per-area conversion, or another independent thickness method. Defect analysis requires sufficient resolution to detect pinholes, cracks, islands, orange-peel texture, edge accumulation, and discontinuities relevant to the intended barrier or active function [137,139].

A defensible image-metrology claim should state what is being measured, why that quantity is functionally relevant, which imaging modality is appropriate, and how the image-derived metric was validated against a physical or food-performance endpoint. Percent surface coverage may support a deposition-uniformity claim, but it does not by itself prove barrier function unless connected to thickness, dry-film continuity, water-vapor or oxygen transfer, microbial response, oil uptake, moisture loss, or shelf-life performance (Table 9). Likewise, apparent color uniformity cannot be used as evidence of homogeneous active-compound distribution unless the optical response has been calibrated and checked against chemical or functional measurements. For defect claims, the minimum detectable defect size and inspection area must be stated in SI units.

Table 9. Minimum reporting and validation matrix for intelligent image metrology in edible coating engineering. The table links imaging tasks to measurable outputs, suitable modalities, likely artifacts and validation requirements.

Imaging Task	Measured Output	Suitable Modality or Approach	Critical Artifacts	Minimum Validation/Reporting Requirement
Droplet and spray characterization	D10, D32, D50, D90, Span, velocity, drift-prone fine fraction	High-speed imaging, shadowgraphy, laser diffraction or calibrated droplet imaging	Motion blur; out-of-plane droplets; threshold bias; evaporation before impact	Report acquisition rate, exposure time, sampling volume, weighting basis, sample size, calibration, velocity basis and replicate variability.
Wet surface coverage	Percent coverage, wet-area fraction, coalescence and local gaps	Controlled RGB/macro imaging, fluorescence-assisted imaging or controlled illumination	Specular highlights; shadows; wet patches; food-color heterogeneity; curved surfaces	Report ROI definition, blank controls, spatial calibration, illumination geometry, segmentation method, ground truth and confidence intervals. When RGB imaging is used, include a color/illumination reference and flat-field correction.
Dry-film continuity	Pinholes, cracks, islands, dry gaps and edge thickening	Microscopy, fluorescence, cross-sectional imaging, profilometry or optical inspection	Resolution below defect scale; drying shrinkage; optical contrast loss	Report defect definition, minimum detectable defect size, defect density per area, replicate surfaces, drying conditions and uncertainty.
Thickness and topography	Mean thickness, thickness coefficient of variation, roughness and edge-thickening ratio	Profilometry, OCT, confocal microscopy, cross-section microscopy or mass-per-area conversion	Porosity; penetration into food; surface curvature; film swelling	Report calibration, measurement grid, wet/dry state, number of profiles or points and independent mass-balance support.

Table 9. *Cont.*

Imaging Task	Measured Output	Suitable Modality or Approach	Critical Artifacts	Minimum Validation/Reporting Requirement
Color, gloss and optical response	Delta E, gloss variation, indicator response and visual uniformity	Calibrated RGB, colorimetry, multispectral or hyperspectral imaging	Illuminant drift; sensor white balance; background; surface wetness	Report color space, white/black calibration, illumination, camera settings, reference target and time after deposition.
Active-compound localization	Spatial distribution of antioxidants, antimicrobials, indicators or carriers	Fluorescence, hyperspectral imaging, chemical mapping or labeled tracer studies	Quenching; leaching; photobleaching; matrix autofluorescence	Report marker chemistry, calibration curve or qualitative status, stability, leaching control, signal-to-noise ratio and functional endpoint.
Drying kinetics	Drying-front velocity, area shrinkage, crack-onset time and wet-to-dry transition	Time-lapse imaging, thermal imaging or gravimetry-coupled imaging	Temperature gradients; airflow variability; surface cooling; changing reflectance	Report time resolution, humidity, temperature, airflow, surface temperature, mass loss and replicate drying runs.
AI segmentation or defect detection	Pixel-level mask, object-level defect counts and class labels	Classical segmentation, U-Net, Mask R-CNN or another validated model	Annotation bias; class imbalance; leakage between images from the same batch	Report split by lot/day/formulation, Dice/IoU, precision, recall, confusion matrix, external validation and failure examples.

Note: Table 9 is a reporting matrix, not a universal standard. The required measurement depth depends on the strength of the claim and on the sensitivity of the coating function to local dose, thickness and defects.

7.2. Imaging Modalities and Selection Logic for Food-Grade Coating Interfaces

The imaging modality should be selected from the coating function backwards. For low-cost screening of surface coverage, controlled RGB imaging may be sufficient if coating-substrate contrast is adequate and lighting is stable. For transparent or weakly contrasted coatings, fluorescence-assisted imaging with food-compatible tracers can improve segmentation, but tracer addition must not alter rheology, surface tension, wetting, drying behavior, active-compound release, or food-contact safety. For smart or responsive coatings, calibrated color or spectral imaging is more appropriate than subjective visual assessment because pH indicators, anthocyanins, and other responsive compounds are sensitive to illumination, matrix color, photobleaching, humidity, and time after deposition [137,139].

For thickness and film-structure claims, surface images are usually insufficient. Dry-film thickness may require profilometry, cross-sectional microscopy, optical coherence tomography, confocal imaging, mass-per-area conversion, or another independent validation route. For irregular foods, two-dimensional (2D) images can overestimate uniformity because valleys, pores, shaded regions, and curved regions may be under-sampled. When the food surface is highly curved or rough, multi-view imaging, structured light, photogrammetry, three-dimensional (3D) reconstruction, or surface-area correction should be considered, especially when coverage or retained solids are normalized by area.

The acquisition system should be reported in enough detail to make the image-derived metric reproducible. The camera model, sensor size or resolution, lens or magnification, working distance, viewing angle, depth of field, exposure time, aperture, illumination geometry, illumination wavelength when relevant, calibration target, file format, compression, white balance, and preprocessing steps should be disclosed. These details are not optional metadata when image-derived variables are used as inputs for AI, CFD validation, digital-twin updating, or process-control decisions [136,142,143].

7.3. Segmentation, Annotation and Validation of Coating Images

Segmentation is often the weakest link in image-based edible coating metrology. Thresholding, color-space segmentation, edge detection, clustering, supervised classification, and deep-learning segmentation can all generate plausible masks, but plausibility is not validation. A segmentation method is valid only to the extent that its output agrees

with a defined ground truth or an independent measurement relevant to the coating claim. The ground truth may consist of expert manual annotation, consensus annotation, physical masks, calibration patterns, chemically labeled coating regions, or independent measurements of retained mass, dry solids, or thickness [139,140].

For irregular foods, the validation set should deliberately include difficult regions: edges, cavities, pores, shadows, specular highlights, wet patches, non-coated regions with similar color, over-coated regions, drainage tracks, cracks, and heterogeneous substrate areas. Reporting only easy images creates an optimistic view of model performance. When manual annotation is used, inter-annotator agreement should be reported or at least checked. If deep-learning segmentation is used, images from the same food item, batch, acquisition day, or formulation should not be split across training and test subsets in a way that creates data leakage [139–141].

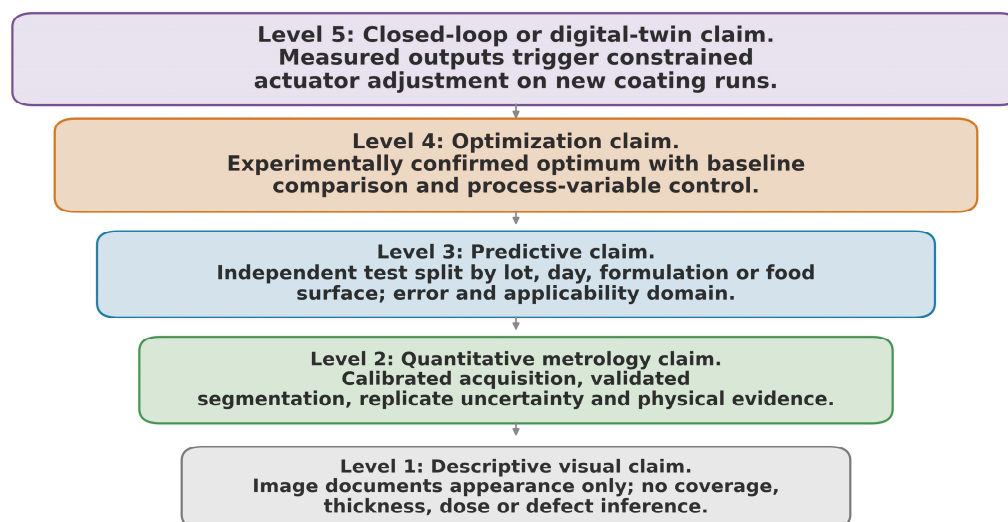
Segmentation performance should be reported using metrics appropriate to the claim. For pixel-level coverage, Dice coefficient, Intersection over Union (IoU), boundary error, and calibration error are more informative than overall accuracy alone, especially when the coated area is highly imbalanced relative to the background. For defect detection, sensitivity, specificity, precision, recall, F1-score, and the false-negative rate should be reported because missing pin-holes or cracks can be more important than slightly overestimating coated area. Representative failure cases should be shown, not only successful segmentations [100,101,139,140].

7.4. Calibration, Uncertainty, Repeatability and Reproducibility

Image-derived coating metrics should be reported with measurement uncertainty. Relevant uncertainty sources include spatial calibration, lens distortion, focus, image compression, illumination drift, sensor noise, exposure settings, sample positioning, surface curvature, ROI selection, segmentation threshold, operator annotation, food-surface heterogeneity, coating transparency, wet-to-dry optical change, and replicate-to-replicate process variation. If these sources are ignored, small differences between formulations or deposition routes may be statistically meaningless [135].

A minimum uncertainty statement should include the number of independent coating runs, number of food items or surfaces, number of images, number of ROIs, calibration method, segmentation-validation metric, and confidence interval or standard deviation of the reported coating descriptor. When image metrology is used to compare deposition technologies, uncertainty should be propagated from image segmentation to coverage, retained area, thickness, or defect metrics. When image-derived variables are used to train AI models, label uncertainty should be treated as a model limitation rather than hidden in the dataset [144,145].

For defensible validation, studies should separate repeatability, reproducibility, and generalization. Repeatability refers to repeated measurements or coating runs under the same setup. Reproducibility refers to comparable results under changed operators, days, instruments, or lots. Generalization refers to performance on new food matrices, new surfaces, new formulations, or new deposition hardware. A model validated only on repeated images from one food lot should not be described as generally applicable to edible coating lines [135,141]. This escalation from descriptive imaging to quantitative metrology, prediction, optimization, and closed-loop or digital-twin claims is organized as a claim-control hierarchy in Figure 7.



The permitted claim must not exceed the weakest validated element: acquisition, calibration, annotation, split design, model validation, uncertainty or food-grade confirmation.

Figure 7. AI claim-control hierarchy for edible coating image metrology. Descriptive images support qualitative discussion, but quantitative metrology, prediction, optimization and closed-loop or digital-twin claims require progressively stronger evidence, including calibrated measurements, independent testing, uncertainty reporting and confirmation on new coating runs.

7.5. AI-Assisted Optimization: Prediction, Active Learning and Multi-Objective Search

AI-assisted optimization in edible coating engineering should be understood as decision support, not as a substitute for controlled experiments. Its most defensible uses are: (a) prediction of coating descriptors from formulation and process variables; (b) segmentation and defect detection in coating images; (c) surrogate modeling for expensive CFD/VOF or experimental coating trials; (d) active learning to select the next most informative experiment; (e) Bayesian or multi-objective optimization to balance competing targets; and (f) closed-loop adjustment of controllable process variables when the feedback signal is validated [25,26,58,61,100–103,136,146].

The input variables should preserve physical meaning. Typical formulation inputs include polymer concentration, solids content, pH, ionic strength, density, apparent viscosity, fitted rheological parameters, surface tension, temperature, active-compound dose, and stability indicators. Typical process inputs include nozzle geometry, pressure, flow rate, gas–liquid ratio, working distance, spray angle, line speed, number of passes, drying temperature, relative humidity, and airflow. Typical image outputs include D32, D50, D90, coverage, thickness coefficient of variation, defect density, retained dry solids, color response, and drying-front metrics. Typical food-performance outputs include oil uptake, moisture loss, oxidation markers, microbial growth, texture, color, sensory acceptance, and shelf-life extension.

Multi-objective optimization is more appropriate than single-response optimization because edible coating design involves trade-offs. A process that maximizes coverage may increase wet mass, drying time, cost, sensory residue, cleaning burden, or microbial risk. A process that minimizes coating use may reduce functional dose or active release. A defensible optimization workflow should therefore define the objective function, constraints, and decision variables before modeling. The main AI/ML use cases, validation boundaries, risks, and permitted claim levels for edible coating engineering are summarized in Table 10.

Table 10. AI/ML use cases, validation boundaries and permitted claims in edible coating engineering. Each use case is constrained by its inputs, outputs, main risk and minimum evidence needed to avoid overclaiming.

AI/ML Use Case	Typical Inputs	Typical Outputs	Main Risk	Minimum Validation/Permitted Claim
Image segmentation	Calibrated images, masks, annotations and lighting metadata	Coverage, masks and defect labels	Learning lighting, background or batch artifacts	Independent test split by lot/day; Dice/IoU; precision/recall; failure examples. Permitted claim: validated image-metrology tool for the studied setup.
Defect detection	Microscopy, RGB or fluorescence images and expert labels	Pinholes, cracks, islands and edge defects	Class imbalance and false negatives	Sensitivity, specificity, F1, minimum detectable defect size. Permitted claim: defect-screening method within defined resolution and substrate range.
Property-performance prediction	Rheology, surface tension, solids, pH and process variables	Coverage, thickness, oil uptake, moisture loss or shelf-life endpoint	Overfitting small formulation datasets	External validation or leave-lot/day/formulation-out testing; baseline comparison. Permitted claim: predictive model for the validated formulation-food-process domain.
Surrogate model for CFD/VOF or experiments	Simulation outputs, experimental droplet data and process variables	Fast estimates of droplet descriptors, deposition flux or coverage probability	Learning simulation bias or invalid boundary conditions	Validation against measured coating outcomes, not only against simulations. Permitted claim: surrogate within the validated operating domain.
Bayesian or active-learning optimization	Candidate formulations, process variables, objectives and constraints	Next experiment, Pareto set or operating window	Optimizing an artifact or unsafe/unfeasible condition	Report acquisition function, feasible domain, stopping rule, uncertainty and confirmation run. Permitted claim: experimentally confirmed optimization within stated constraints.
Digital twin or closed-loop control	Sensor stream, calibrated model, control variables and endpoint target	Updated prediction and constrained process adjustment	Calling a static model a digital twin	Online or batch updating, validated feedback signal and confirmation on new runs. Permitted claim: roadmap level unless closed-loop validation is shown.
Explainable AI and diagnosis	Feature importance, SHAP/LIME-type summaries, process metadata	Ranked drivers, failure hypotheses and process windows	Interpreting correlation as mechanism	Use as hypothesis support, checked against physical knowledge and designed experiments. Permitted claim: interpretive support, not mechanistic proof.

7.6. Data Structure, Leakage Control, Explainability and Documentation

AI-ready edible coating data should be structured around the physical experiment rather than around images alone. At minimum, each image or measurement record should be linked to the formulation batch, food matrix, cultivar or product type when relevant, surface preparation, deposition route, nozzle or actuator settings, fluid properties, drying conditions, acquisition settings, calibration file, annotation protocol, replicate identifier, and food-performance endpoint. This hierarchy is necessary to avoid leakage and to design validation splits that test generalization rather than memorization [103,141,144,145].

Data leakage is particularly likely in coating-image datasets because images from the same coated food item, production lot, acquisition day, or formulation may look highly similar. Random image-level splitting can therefore produce inflated test performance if the same physical experiment contributes images to both training and testing. When generalization is claimed, splitting should be performed at the most conservative level required by the claim: food item, coating run, lot, day, formulation, surface type, or deposition hardware. The split design should be reported explicitly [141].

Explainable AI may help identify whether predicted coating performance is driven by physically meaningful variables such as viscosity, solids, surface tension, flow rate, droplet size, coverage, or drying conditions. However, feature importance is not mechanistic proof. Explanations should be interpreted as diagnostic support and checked against coating

physics, designed experiments, and independent measurements. If the model relies mainly on lighting, background, camera exposure, food color, or batch identity, the result should be reported as a limitation rather than as a scientific discovery.

Dataset and model documentation should be treated as part of the scientific method. A dataset card or datasheet should describe motivation, composition, acquisition protocol, inclusion and exclusion criteria, annotation process, known biases, recommended use, prohibited use, and maintenance status. A model card should describe model architecture, training data, validation data, intended use, limitations, performance by subgroup or surface type, failure modes, and extrapolation boundaries. These practices are consistent with broader recommendations for transparent dataset and model reporting [144,145].

8. Food Performance and Smart Edible Interfaces

Food performance is where coating engineering becomes meaningful. The same formulation can produce different outcomes depending on food geometry, porosity, surface moisture, roughness, lipid content, processing temperature, and storage environment. Fried foods require attention to oil uptake, moisture retention, crust formation, color, and texture. Fruits and vegetables require control of dehydration, respiration, firmness, microbial stability, and surface appearance. Meat and seafood require oxidation, microbial, and sensory endpoints. Bakery products require water activity, moisture migration, and texture. Dairy products may require mold control, dehydration control, and sensory validation [1,13–15,20,30,57,89,96,147,148].

For model-informed edible coating engineering, food-performance endpoints should be explicitly linked to deposition-state variables. DPM-predicted deposition flux, measured surface coverage, retained solids per unit area, wet/dry-film thickness, defect density, and coating continuity should be statistically connected to oil uptake, moisture loss, respiration, microbial counts, oxidation, color, texture, or sensory acceptance, depending on the food matrix. This prevents digital-twin or AI outputs from becoming detached from the food-quality endpoints that justify the coating.

The main food-performance endpoints that should be linked to deposition and coating-structure variables are summarized in Table 11 [89,96,97].

Table 11. Food-performance endpoints linked to coating engineering variables. The endpoints should be statistically connected to retained dose, coverage, thickness, continuity, defects and drying history rather than interpreted from formulation alone.

Food System	Main Problem	Coating Logic	Critical Endpoints
Fried foods	Oil uptake and moisture loss	Protein/polysaccharide barrier; controlled spray or flow-blurring	Oil uptake, moisture retention, texture, color, sensory acceptance.
Fruits and vegetables	Dehydration, respiration and microbial spoilage	Polysaccharide/lipid/active coatings; dipping or spray	Weight loss, firmness, respiration, microbial counts, appearance.
Meat and seafood	Oxidation and microbial growth	Chitosan/protein/active coatings; spray/electrostatic	TBARS, microbial counts, color, odor, sensory quality.
Bakery products	Moisture migration and texture loss	Hydrocolloid/protein coatings; localized spray	Water activity, texture profile, staling, sensory quality.
Cheese and dairy surfaces	Mold, dehydration and surface defects	Protein/lipid/antimicrobial coatings; multilayer spray	Shelf life, mold growth, moisture loss, flavor.

Smart edible coatings should be framed carefully [9,13,14]. A coating may be edible, biodegradable, active, intelligent, or food-contact, but these categories are not interchangeable. Colorimetric indicators, pH-responsive systems, antimicrobial release systems, antioxidant release layers, and biosensing concepts are promising, but edible sensor-like interfaces require safety, migration, toxicology, allergenicity, sensory, stability, and data-interpretation

validation. The strongest concept is not that all coatings become sensors, but that some edible coatings may evolve from passive barriers into data-generating food interfaces under defined safety constraints [81–83].

From Active Coatings to Data-Generating Edible Interfaces

The most realistic near-term transition is not from passive coatings directly to fully autonomous sensor coatings, but from passive barriers to active, measurable, and partially data-generating interfaces. In this intermediate stage, coatings can be engineered to provide controlled release, measurable color change, local antimicrobial action, or surface-state information, while still requiring external validation through microbiology, sensory analysis, migration testing, and stability assessment [13,14,81–83].

When smart or colorimetric edible interfaces are used as data-generating layers, their optical or chemical signal should be treated as a calibrated proxy rather than as direct proof of freshness, safety, or shelf-life extension. Signal drift, false-positive or false-negative responses, pigment migration, toxicological exposure, sensory interference, and calibration against microbiological, chemical, and sensory endpoints should be reported before such signals are integrated into a digital-twin decision layer.

This distinction improves the logic of the review because it avoids conflating edible, active, intelligent, and smart systems. A coating can be edible without being active; active without being intelligent; intelligent as a food-contact indicator without being edible; or edible and functional without being suitable for live supply-chain monitoring. Each claim must therefore be tied to the specific function demonstrated experimentally [1,13–15,20,30,57,81–83,147].

Regulatory interpretation should distinguish edible ingredient status, intentional food-additive or Generally Recognized as Safe (GRAS) status, food-contact material status, migration potential and Good Manufacturing Practice (GMP) compliance according to the target jurisdiction.

9. Industrial Translation: Safety, Regulation, Sustainability and Economics

The industrial translation and patent-aware roadmap is summarized in Figure 8.

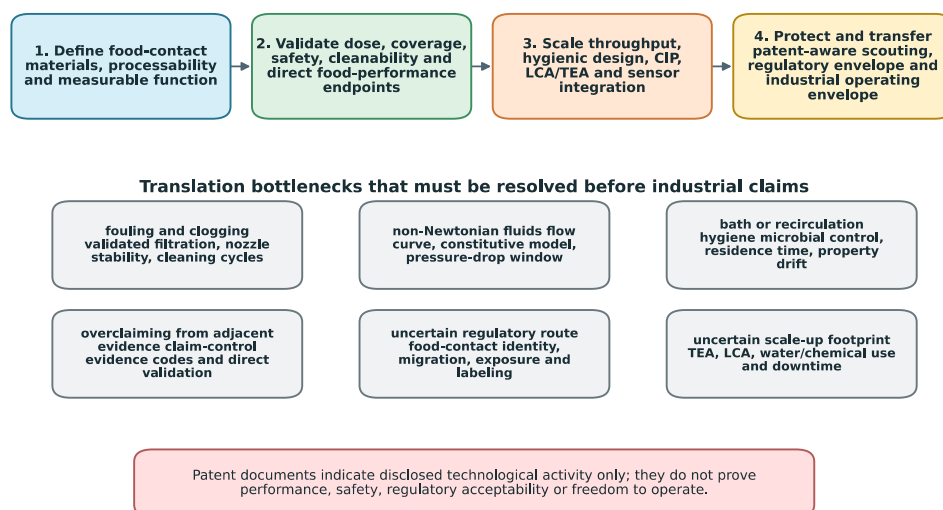


Figure 8. Industrial translation and patent-aware technology roadmap. The roadmap connects processability, dose and coverage validation, food-contact safety, cleanability, scale-up, CIP, LCA, TEA, sensor integration and patent-aware scouting. Patent documents are interpreted as technology signals only and do not establish performance, regulatory acceptability or freedom to operate.

Industrial adoption requires more than proof that a coating improves a laboratory endpoint. It requires throughput, pumpability, nozzle stability, CIP, sanitation, microbial safety, in-line sensors, process analytical technology (PAT)-style monitoring, equipment cost, maintenance, and operator safety. Protein, polysaccharide, and lipid-containing formulations may adhere to wetted surfaces, feed lines, and nozzles; therefore, cleaning validation is central to scale-up, not peripheral [13,19,21,23,30,50,57,85,86,149,150].

Active, antimicrobial, antioxidant, smart, and nano-enabled edible coatings require rigorous safety evaluation based on composition, functionality, interaction mechanisms, and application conditions. Their natural, edible, or biodegradable origin provides opportunities for sustainable and food-compatible design, but it does not itself establish safety. Safety depends on the identity, purity, dose, migration, exposure, allergenicity, toxicology, particle size, intended use, food matrix, and consumer group [21,149]. Natural extracts, essential oils, antimicrobial compounds, nanoparticles, and responsive indicators require food-contact safety and regulatory justification. Good Manufacturing Practice (GMP), Hazard Analysis and Critical Control Points (HACCP), and CIP logic should be integrated early in process design [78,86,151]. Cleaning validation should report cleaning time, water and chemical use, rinse conductivity or TOC, residual protein/allergen swabs when relevant, microbial counts, visual residue score, and acceptance limits.

Sustainability should also be quantified rather than assumed [23,150,152–155]. A coating derived from circular materials may still require high water use, energy-intensive drying, purification, chemical modification, cleaning burden, or expensive equipment. LCA and TEA should report material consumption per coated kilogram, water and energy use, drying demand, wastewater, cleaning chemicals, shelf-life extension, food-loss reduction, cost per coated kilogram, and comparison with conventional packaging or preservation alternatives [49,128,149,152–158].

The principal industrial barriers and engineering responses for scale-up are summarized in Table 12 [49,50,158].

Table 12. Industrial barriers and engineering responses for scalable edible coating implementation. The barriers translate laboratory formulation success into process, hygiene, safety, regulatory, economic and monitoring requirements.

Barrier	Cause	Engineering Response
Clogging	Solids, gelation, aggregates or fibers	Filtration, rheological control, removable nozzle and cleaning validation.
Droplet variation	Unstable pressure, flow rate or viscosity drift	Sensors, flow control and image-based monitoring.
Low uniformity	Irregular geometry and shadowed regions	Vision-guided trajectories and coverage feedback.
Contamination	Residues in lines or baths	Good Manufacturing Practice (GMP), HACCP and CIP.
High cost	Specialized equipment and low throughput	Modular scale-up and TEA.
Weak sustainability claim	Circular source without quantified impact	LCA and food-loss reduction metrics.

9.1. Regulation-by-Design and Safety-by-Design

A regulation-by-design approach should define safety constraints before the deposition route is selected. Food-contact status, ingredient identity, concentration, intended consumption, vulnerable population, allergenicity, migration potential, nanoparticle exposure, and cleaning residues must be considered early. For each intended use, authors should specify the target jurisdiction, ingredient regulatory pathway, migration-testing logic, allergen-labeling implication, exposure level, and whether the coating is consumed as an edible layer or functions as a food-contact layer. Recent reviews emphasize that commercialization barriers include not only technical performance, but also regulatory support, consumer acceptance, safety, circular feedstock feasibility, and scalability [13,21,23,50,85,86,149].

Safety-by-design is also necessary for AI-guided and smart coatings. A prediction model may optimize shelf life or coverage, but it should not recommend a formulation

or process condition that violates ingredient limits, creates unacceptable sensory changes, increases microbial risk, compromises cleaning, or generates misleading freshness indicators. Therefore, optimization constraints should include safety, sanitation, and regulatory boundaries as hard limits [9,21,26,50,57,74,75,80,115,129–133].

9.2. LCA and TEA as Translation Filters

LCA and TEA should be used as translation filters, not as decorative sustainability statements. A coating can reduce food loss but still be unattractive if it requires high water consumption, energy-intensive drying, expensive purification, excessive cleaning chemicals, uncertain waste-derived feedstock consistency, or low-throughput equipment [23,150]. Conversely, a coating with modest barrier performance may be valuable if it reduces waste, uses low-cost by-products, and fits existing lines with limited capital expenditure [49,157,158]. Each LCA or TEA claim should specify the functional unit, system boundary, allocation rule, baseline comparator, shelf-life-gain assumption, cleaning burden, and uncertainty or sensitivity scenario.

Recent techno-economic evidence for a cellulose-based edible fruit coating from banana stem illustrates why scale, utility integration, and raw-material valorization materially affect feasibility; the reported production cost decreased at a larger capacity, and pinch analysis reduced utility consumption [150]. For edible coating engineering, the relevant economic units should therefore be cost per coated kilogram, cost per shelf-life day gained, coating solids used per kilogram of food, and avoided food loss, rather than formulation cost alone [49,157,158].

10. Patent-Aware Roadmap and Minimum Reporting Checklist

10.1. Patent-Aware Innovation Opportunities

The patent-aware technological scan identifies innovation opportunities, not legal clearance. The roadmap-level opportunities identified by the scan include adjustable flow-blurring atomizers for edible coating fluids, vision-assisted spray deposition, multiphase digital-twin workflows, localized smart edible layers, CIP-compatible deposition hardware for biopolymer fluids, and multi-objective optimization methods linking lower oil uptake, lower coating waste, higher coverage, and longer shelf life. These directions should be treated as innovation domains that require patent-family verification, freedom-to-operate review by qualified specialists, and food-specific validation before commercial translation [33,34,36,37,39,50].

A more detailed commercialization-oriented interpretation is provided in Supplementary Data S3, where patent-aware signals are classified by food substrate, edible coating material, deposition/control route, digital-twin relevance, maturity signal and limitation.

The next generation of edible coatings is likely to depend on the integration of advanced formulation strategies with controlled deposition, physically interpretable metrology, validated multiphase modeling, and scale-aware decision frameworks for engineered edible interfaces. The evidence synthesized in this review supports a clear shift from formulation-first development toward precision edible coating engineering, in which the functional value of a coating depends on the entire droplet-to-film-to-function chain. This shift has practical consequences: research investment should prioritize not only new biopolymer sources and active ingredients, but also the measurement systems, atomization physics, modeling credibility, and process-control architectures needed to translate laboratory formulations into reproducible food-grade coating technologies [13,19,22,25,30,33–36,57,58,61,124–127,147].

10.2. Staged Roadmap for Research and Translation

The roadmap is staged because digital-twin-ready workflows are not yet mature for routine edible coating production lines. A realistic strategy is to first establish reporting standards, validated formulation and deposition inputs, calibrated image metrology, uncertainty reporting and food-specific performance datasets. Only after these elements are available can bounded surrogate models, decision-support tools or closed-loop pilot systems be evaluated responsibly [13,19,21,25,30,33,36,57,58,61,124–127].

The staged research and translation roadmap proposed by this review is presented in Supplementary Table S2 [25,58,103].

For this reason, patent signals involving digital twins, Artificial Intelligence (AI), computer vision or closed-loop control are interpreted as roadmap-level innovation signals unless they are linked to a defined food substrate, edible coating material, deposition route, measured coating quality, validated food-performance endpoint, cleaning logic and feedback-control layer.

Phase 1 should receive the earliest methodological priority. Without this foundation, neither AI models nor digital twins can be meaningfully generalized. Phase 2 should concentrate resources on the mechanistic bottlenecks that most often block scale-up: non-Newtonian atomization, time-dependent surface tension, fouling, nozzle-to-nozzle variability, and the mismatch between simplified Newtonian models and real food-grade biopolymer fluids. Phase 3 should then integrate validated models with image-based decision layers and pilot-scale equipment, with emphasis on coating uniformity, hygienic design, Good Manufacturing Practice (GMP), Hazard Analysis and Critical Control Points (HACCP), and CIP compatibility. Only after these milestones are achieved should the field move decisively into Phase 4, where closed-loop or semi-autonomous production lines can be defended on technical, economic, and regulatory grounds [13,21,25,30,33,36,50,57,103,124–127,159].

10.3. Minimum Reporting Checklist

A concise reporting checklist is summarized in the main text, while the extended minimum reporting checklist is provided as Supplementary Table S3 and the representative-study reporting audit is provided as Supplementary Data S2 [25,58,103].

11. Limitations of This Review

This review is a critical narrative review supported by open evidence mapping; it should not be interpreted as a PRISMA systematic review, meta-analysis, or formal Scopus/Web of Science bibliometric study. OpenAlex metadata were used to identify thematic intersections and fragmentation, but source-level claims were assigned only after manual curation. The curation descriptors reported in this review document scoping and claim-control decisions and should not be interpreted as journal-level or database-equivalent citation metrics.

A second limitation is the heterogeneous maturity of the evidence base. Direct edible coating evidence is strong for several formulation and preservation endpoints, but evidence for microfluidic droplet generation, flow-blurring atomization, closed-loop AI control, and food-grade digital twins is still uneven and often transferred from adjacent engineering fields. These concepts are therefore treated as mechanistic support or roadmap-level opportunities unless direct food-coating validation is available.

A third limitation concerns translation. Patent documents, LCA/TEA concepts, and regulatory considerations indicate relevant design constraints, but they do not prove industrial readiness, food-contact acceptability, sensory acceptance, freedom to operate, or economic viability. Future studies should close these gaps through normalized dose

comparisons, calibrated metrology, pilot-scale hygienic trials, safety-by-design evaluation, and transparent uncertainty reporting.

12. Conclusions

Edible coatings should be assessed as deposited functional interfaces rather than only as cast-film chemistries or empirical preservation treatments. Their performance depends on a linked chain of formulation properties, rheology, interfacial dynamics, deposition route, droplet formation, impact, retained dose, wet-film evolution, drying, dry-film structure, and food-specific function. Without intermediate measurements of retained solids, coverage, thickness, defects, and uncertainty, preservation outcomes cannot be reliably attributed to formulation alone.

Precision deposition is not intrinsically superior to dipping or conventional spraying. Each route, including dipping, pneumatic spraying, ultrasonic atomization, electrostatic spraying, flow-blurring, microfluidic carrier generation, and robotic deposition, has specific advantages, limitations, and validation requirements. A route should be considered fit for purpose only when it delivers the required functional dose with measurable coverage, acceptable transfer efficiency, controlled defects, validated cleanability, and reproducible food-performance benefits.

Image metrology, CFD/VOF modeling, surrogate models, and AI-assisted optimization can strengthen edible coating research when they are connected to calibrated measurements and independently validated outcomes. For most edible coating applications, digital twins and closed-loop control should currently be framed as digital-twin-ready or roadmap-level architectures rather than established industrial practice.

Future work should prioritize normalized dose comparisons, food-specific droplet-to-film validation, uncertainty-aware imaging, hygienic equipment design, regulation-by-design, and quantitative LCA/TEA. This shift would move edible coating research from formulation-centered promise toward reproducible, measurable, and scalable coating technologies.

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Nomenclature

CFD	Computational Fluid Dynamics
VOF	Volume of Fluid
CIP	Cleaning In Place
TEA	Techno-Economic Analysis
LCA	Life Cycle Assessment
DPM	Discrete Phase Model
AI	Artificial Intelligence
ML	Machine Learning
Re	Reynolds number
We	Weber number
Oh	Ohnesorge number
Ca	Capillary number
Bo	Bond number
Pe	Péclet number

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