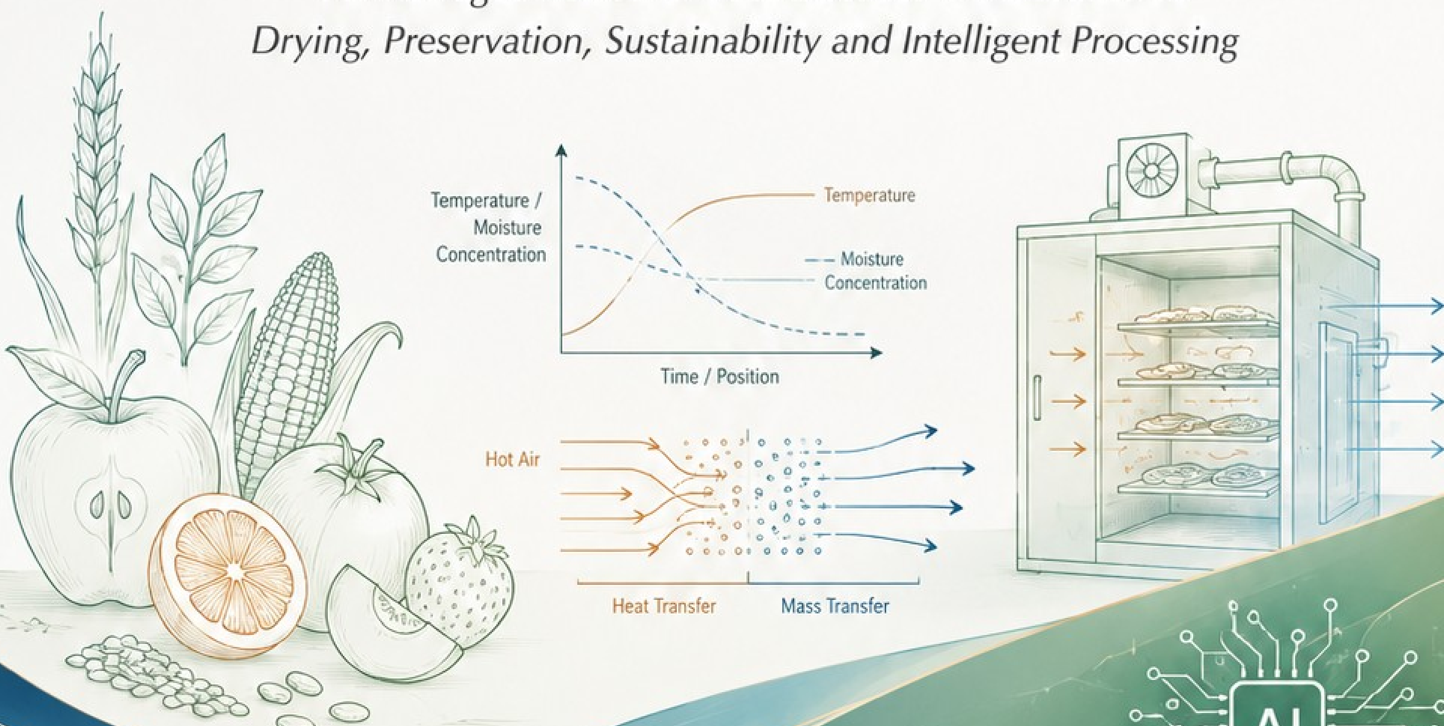
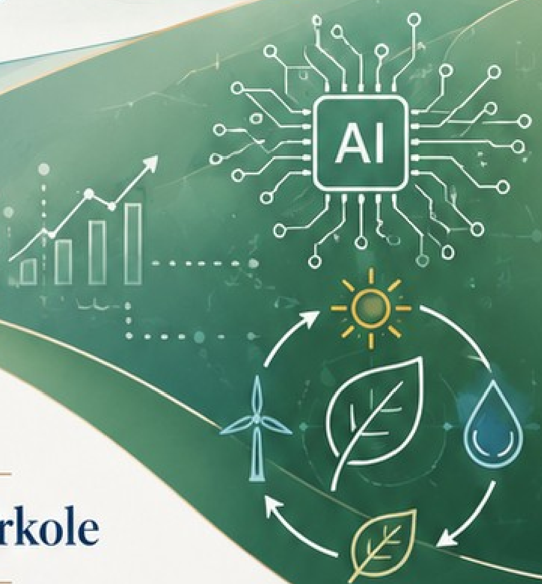
Research Contributions of Professor Arun S. Mujumdar to Food Science and Technology

An Abridged Review of Four Decades of Innovation in Drying, Preservation, Sustainability and Intelligent Processing





Compiled by

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Scope of this edition

This abridged monograph is a thematic and interpretive review of selected books, chapters and peer-reviewed publications. It is not intended as a complete bibliography or a formal citation-impact analysis. The emphasis is on the evolution of ideas, their relevance to food engineering practice, and their continuing influence on sustainable and intelligent food processing.

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Executive Summary

Professor Arun S. Mujumdar's contribution to food science and technology is best understood not as a sequence of isolated inventions, but as the construction of an international intellectual framework for drying. Across more than four decades, his work has connected transport phenomena, dryer design, food quality, energy efficiency, process control and, more recently, artificial intelligence and additive manufacturing. This framework has helped move dehydration from a largely empirical preservation operation toward a science-based, quality-oriented and increasingly data-driven manufacturing platform.

His most visible scholarly achievement is the sustained codification of drying knowledge. The multi-edition Handbook of Industrial Drying became a major reference across chemical, mechanical, agricultural and food engineering, while Drying Technologies in Food Processing and the open-access Drying of Foods, Vegetables and Fruits volumes brought fundamentals and emerging applications directly to food scientists, equipment designers, students and practitioners [1-3]. These works emphasize a recurring message: no dryer is universally optimal; selection must account for material structure, moisture-binding mechanisms, heat sensitivity, desired quality, throughput, energy source, safety and economics.

In food applications, Mujumdar's research network helped establish a quality-centered view of dehydration. The relevant endpoint is not simply a target moisture content. It is a stable and safe product with acceptable color, flavor, nutrients, texture, porosity, rehydration behavior and microstructure. Reviews and collaborative studies on high-quality drying, pretreatments, microwave hybrids, ultrasound-assisted convection and low-temperature technologies provided structured comparisons of how process conditions and equipment choices affect these attributes [4-8].

A second major contribution is the promotion of hybridization and process intensification. Rather than treating hot-air, heat-pump, microwave, infrared, vacuum, freeze-drying, superheated-steam and physical-field-assisted techniques as competing technologies, his publications repeatedly examine how they can be staged or combined to exploit complementary strengths. This systems perspective supports shorter drying times, reduced thermal exposure, better product uniformity and lower energy use, while recognizing scale-up, control, capital cost and safety constraints.

A third theme is intellectualization. The widely cited review on artificial intelligence in fresh-food drying synthesized the use of artificial neural networks, fuzzy logic, expert systems, computer vision and electronic sensing for prediction, optimization and control [9]. Later work extended this trajectory toward low-carbon process selection, lifecycle thinking, cost-reduction algorithms and AI-assisted additive manufacturing [10-12]. In this view, digital tools are not substitutes for transport theory; they are complementary methods for handling nonlinear interactions, noisy quality data and real-time decision-making.

The newest phase of his food research addresses 3D and 4D printing. Here, his established expertise in drying becomes newly relevant: printed structures often require post-processing to stabilize shape, develop crispness, control porosity, ensure safety and create programmed responses. Collaborative publications on printed foods, internal architecture, freeze-dried snacks, multidimensional printing and foods for special medical purposes link formulation, rheology, geometry, drying and personalized nutrition [13-19].

Professor Mujumdar's global legacy therefore has three dimensions. Scientifically, he helped define drying as a coupled transport-and-quality problem. Institutionally, he built journals, books, conferences and open educational resources that made drying knowledge globally accessible. Professionally, he mentored an unusually broad network of researchers across Asia, Europe, the Americas and elsewhere, accelerating the transfer of ideas between universities and industry. His influence on food processing is most evident in the way contemporary engineers now evaluate drying systems: by balancing safety, quality, energy, carbon, cost, controllability and product functionality rather than optimizing moisture removal alone.

Table 1. Main research themes and enduring contributions

Research theme	Representative contribution	Enduring significance
Drying fundamentals	Coupled heat and mass transfer, kinetics, psychrometry, material-dependent dryer selection	Made food drying a rigorous systems-engineering problem rather than an empirical unit operation
High-quality dehydration	Comparison of convective, freeze, microwave, infrared, heat-pump and hybrid routes	Shifted optimization toward color, nutrients, texture, rehydration and microstructure
Pretreatment and intensification	Thermal, chemical and non-thermal pretreatments; physical-field assistance	Reduced time and thermal damage while exposing trade-offs in nutrient loss, residues and scale-up
Modelling and AI	ANN, fuzzy logic, machine vision, sensing, optimization and advanced control	Enabled prediction and adaptive operation for nonlinear, variable food materials

Research theme	Representative contribution	Enduring significance
Sustainability	Energy/exergy thinking, heat recovery, clean energy, lifecycle and low-carbon selection	Linked process engineering decisions to resource use, emissions and food-system resilience
Additive manufacturing	Printability, internal structure, post-processing, 4D response and medical foods	Connected geometry and personalized nutrition with drying-based stabilization and texture design
Knowledge infrastructure	Handbooks, specialist books, open e-books, Drying Technology and IDS	Created a global platform for education, standardization, collaboration and industrial diffusion

1. Introduction: A Career Built Around Drying as a Systems Problem

Drying is among the oldest methods of food preservation, yet it remains one of the most technically demanding operations in modern food manufacturing. A wet food is a multicomponent, deformable and often biologically active material. As moisture leaves, temperature, water activity, composition, porosity, stress, glass transition, enzymatic activity and reaction rates change simultaneously. The equipment must also manage airflow, humidity, residence time, product loading, fouling, dust, fire risk and energy consumption. Professor Arun S. Mujumdar's central achievement has been to insist that these interacting phenomena be treated together.

His early work arose from classical transport phenomena and industrial drying. This foundation was broader than food engineering, covering particles, pastes, slurries, sheets and porous solids. That breadth proved especially valuable when applied to foods because no single material model can adequately describe fruits, vegetables, grains, dairy powders, seafood, herbs, nutraceuticals and structured products. The Handbook of Industrial Drying, first issued in the 1980s and repeatedly expanded, captured this diversity and became a bridge between fundamental science, equipment design and sector-specific practice [1].

Over time, his research philosophy developed several recognizable principles. First, dryer selection must be product-specific. Second, product quality and energy use are coupled rather than independent objectives. Third, emerging technologies should be assessed by realistic comparisons with established systems, including scale, reliability, safety and cost. Fourth, hybrid processes often offer more practical benefits than a single "advanced" energy source. Fifth, dissemination is part of research impact: useful knowledge must be organized, peer reviewed and made accessible to engineers who can implement it.

This last principle explains why books, book chapters, journal editorship, conferences and international mentoring are integral to his scientific legacy. His website describes a global Transport Processes Research group linking collaborators from many countries and notes a long-running effort to distribute peer-reviewed e-books freely [20]. The food-science contribution is therefore both technical and infrastructural: it includes what was discovered, how the field was organized, and how expertise was transferred across regions.

2. Scientific Foundations: Heat, Mass and Momentum Transfer

At the heart of Mujumdar's work is the recognition that drying rate is governed by interacting external and internal resistances. External transfer depends on the velocity, temperature, humidity and flow pattern of the drying medium. Internal transfer depends on product geometry, pore structure, phase state, shrinkage, capillary movement, diffusion, vapor pressure and the binding of water to macromolecules. In many foods, the falling-rate period dominates, meaning that raising air temperature or velocity eventually gives diminishing returns because internal moisture migration becomes controlling.

This distinction has practical consequences. Increasing temperature may accelerate evaporation but can produce case hardening, collapse, surface discoloration, volatile loss or excessive thermal exposure. Increasing velocity can improve external coefficients but may add fan energy without overcoming internal resistance. Reducing pressure can lower boiling temperature, but vacuum systems add capital and sealing requirements. Microwave or radio-frequency energy can generate volumetric heating, yet field nonuniformity and thermal runaway must be controlled. Heat-pump drying offers low-temperature dehumidification and heat recovery but requires careful matching of refrigeration performance and product load.

The books edited by Mujumdar translate these trade-offs into design logic. Drying Technologies in Food Processing, for example, places food fundamentals, water activity, biological changes, spray drying, low-pressure superheated-steam drying, heat-pump drying, freeze/vacuum drying, post-drying operations, control and safety within one volume [2]. This structure itself is significant: it demonstrates that a commercial drying process is not only a heat-and-mass-transfer device but a linked sequence from raw material preparation to safe storage.

Mathematical modelling appears throughout this body of work not as an end in itself but as a way to connect measurable properties with design decisions. Thin-layer equations can summarize kinetics and enable preliminary comparison. Diffusion models can estimate effective moisture transport. Computational fluid dynamics can reveal maldistribution, recirculation zones and nonuniform heat transfer. Population balances and particle models assist spray and fluidized-bed systems. The most useful models, in Mujumdar's tradition, are those that support scale-up, control or technology selection while remaining transparent about assumptions and uncertainty.

3. Thermal Dehydration and the Evolution of Dryer Technology

Conventional hot-air drying remains dominant because it is simple, scalable and compatible with many product forms. Mujumdar's publications do not dismiss convection; instead, they identify where it performs well and where limitations justify intensification. Good convective design requires uniform airflow, appropriate loading, controlled humidity and temperature schedules, and attention to product thickness and orientation. Poor distribution can cause simultaneous under-drying and over-drying within the same batch, a quality and safety failure that cannot be corrected by merely extending total time.

Heat-pump drying is an important example of the systems approach. By dehumidifying and reheating process air in a closed or semi-closed loop, heat pumps enable lower-temperature operation and recovery of latent and sensible heat. Mujumdar's chapter with Islam in Drying Technologies in Food

Processing helped frame heat-pump drying as a practical method for heat-sensitive foods rather than simply a refrigeration application [2]. Its benefits are strongest when the product value justifies tighter control and when the system operates for sufficient hours to offset capital cost.

Superheated-steam drying illustrates another recurring theme: changing the drying medium can alter both energy integration and product chemistry. In an oxygen-limited environment, oxidation may be reduced; steam can be recovered or integrated with other thermal operations; and at appropriate conditions heat-transfer rates can be high. At the same time, inversion temperatures, condensation during startup, pressure control and product-specific reactions complicate design. Mujumdar's handbooks and chapters helped bring superheated-steam concepts into mainstream drying education, including food applications and lower-pressure variants.

Microwave-, infrared-, radio-frequency- and ultrasound-assisted drying shift energy or momentum closer to the controlling resistance. Microwave heating can accelerate internal vapor generation; infrared can deliver rapid surface heating; radio frequency offers deeper penetration in some materials; and airborne ultrasound can disrupt boundary layers and promote internal transport. The critical reviews co-authored by Mujumdar emphasize that these methods are most credible when evaluated as parts of hybrid systems. Microwave-assisted convective or vacuum drying, for example, can shorten the slow final stage, while freeze-drying followed by controlled microwave input can reduce time without surrendering the porous structure associated with sublimation [7,8].

Freeze-drying occupies a special place in quality-oriented food preservation. It minimizes liquid-phase transport and typically gives excellent shape retention, porosity and rehydration, but its energy use, vacuum requirements and long cycles restrict it to higher-value products. Mujumdar's recent contribution to a dedicated freeze-drying volume continues a long-standing effort to improve cycle efficiency, heat transfer and product quality [19]. The research challenge is not to declare freeze-drying universally superior, but to identify when its quality premium exceeds its economic and environmental cost.

4. Preservation of Fruits, Vegetables and Other High-Value Foods

Fruits and vegetables are ideal test materials for drying science because they combine high initial water content with cellular structure, heat-sensitive pigments, enzymes, organic acids, sugars, vitamins and volatile compounds. Their behavior also varies with cultivar, maturity, tissue orientation and pretreatment. Mujumdar's collaborative work with major food-engineering groups in China, Southeast Asia, Canada and elsewhere generated a broad comparative literature on these materials.

The 2017 review on high-quality drying of vegetables, fruits and aquatic products articulated a demanding performance standard: efficiency and economy must be balanced with flavor, nutrients, color, rehydration, uniformity, appearance and texture [4]. It evaluated infrared, microwave, radio-frequency, electrohydrodynamic and hybrid approaches, helping researchers compare technologies through quality outcomes rather than novelty alone. This quality-centered framework became influential because it matched the needs of processors of premium snacks, ingredients and rehydratable products.

Pretreatment is a second major avenue. Blanching can inactivate enzymes and alter tissue permeability; osmotic treatment can remove part of the water while introducing solutes; freezing can create pathways through cell disruption; ultrasound and pulsed electric fields can enhance mass transfer; and acid, alkali, sulfite, ozone or carbon dioxide treatments can influence color, kinetics or microbial status. The comprehensive review led by Deng and co-authored by Mujumdar compared these options while drawing attention to trade-offs such as soluble-solid loss, chemical residues, texture damage and process complexity [5].

Airborne ultrasound provides a useful example of a non-thermal intensification method. The review by Fan, Zhang and Mujumdar reported that ultrasound-assisted convection can shorten drying time, raise effective diffusivity and mass-transfer coefficients, and in some cases better preserve color, nutrients and microstructure than unassisted convection [6]. Yet the work also highlights the need to understand equipment geometry, acoustic coupling, energy efficiency and scale. This balanced treatment - promise accompanied by engineering conditions for success - is typical of Mujumdar’s reviews.

Beyond produce, his food-related publications address aquatic products, ready-to-eat foods, space foods, powders, herbs, mushrooms and functional ingredients. The 2023 review on advanced ready-to-eat foods positions dehydration as an alternative or complement to frozen distribution and chemical preservation, with emerging relevance to personalized foods and foods for special medical purposes [10]. This broadens the preservation objective: drying is not only a means of extending shelf life, but a platform for creating lightweight, convenient and functionally designed food systems.

5. Quality of Dried Foods: From Moisture Removal to Product Design

One of the most consequential shifts in modern drying research is the movement from “removal of water” to “engineering of product state.” Mujumdar’s publications helped normalize this shift. Moisture content and water activity remain essential for stability, but they do not fully describe a dried food. A product can meet a moisture specification yet fail because of browning, oxidation, loss of aroma, poor rehydration, excessive hardness, collapse, caking or nonuniformity.

Color is affected by pigment degradation, enzymatic and nonenzymatic browning, oxidation and local overheating. Nutrient retention depends on temperature-time history, oxygen exposure, pretreatment and matrix protection. Texture emerges from cell-wall modification, pore formation, shrinkage, glass transition and internal stress. Rehydration reflects both chemical affinity for water and the survival of pathways through which water can return. Aroma retention depends on volatility, binding and the movement of vapor during drying. These attributes are coupled, so optimizing one can damage another.

Mujumdar’s quality-focused reviews encourage the use of multiresponse optimization. A lower temperature may improve color but extend exposure and increase energy use. A rapid microwave finish may improve throughput but create hotspots. High porosity may enhance crispness or rehydration but reduce mechanical strength and packaging stability. Pretreatment may improve color and kinetics but alter flavor or composition. The correct outcome therefore depends on the intended product: a crisp snack, an instant soup inclusion, a powder, a medical food and a shelf-stable ingredient have different target structures.

Microstructure became increasingly important in his later collaborations. Imaging and texture analysis show how cell collapse, pore size, wall thickness and printed infill determine macroscopic behavior. This connection is especially visible in 3D-printed foods, but it also applies to conventional slices, foams, granules and powders. In effect, drying is a form of materials processing in which water removal and structure formation occur together.

6. Modelling, Process Optimization and Intelligent Control

Food drying is difficult to control because the raw material is variable and many important states cannot be measured directly in real time. Surface temperature may not represent the interior. Exhaust humidity reflects the whole chamber rather than each item. Color and shrinkage can change rapidly near the endpoint. Traditional control based only on inlet temperature and elapsed time therefore leaves substantial uncertainty.

Mujumdar's work spans the progression from mechanistic modelling to data-driven intelligence. Mechanistic models explain transport and support extrapolation. Empirical models fit kinetics efficiently. Response-surface methods and design of experiments identify influential factors. Artificial neural networks approximate nonlinear input-output relations when data are sufficient. Fuzzy systems encode expert judgment where boundaries are not sharp. Computer vision and electronic sensing provide quality-related signals, while optimization algorithms search for operating schedules that balance multiple objectives.

The 2019 review by Sun, Zhang and Mujumdar was pivotal in consolidating this field [9]. It surveyed neural networks, fuzzy logic, expert systems, electronic noses and computer vision for modelling, prediction and optimization of heat and mass transfer, thermodynamic performance and product quality. Its significance lies in treating AI as part of drying engineering rather than a disconnected computational exercise. The variables of interest remain physical - moisture, temperature, energy, color, texture and composition - even when the mapping is learned from data.

This integration supports several industrial functions. Soft sensors can estimate moisture or quality attributes from temperature, humidity, weight, images or spectra. Predictive models can identify the endpoint before over-drying occurs. Supervisory control can change temperature, humidity, pressure or power by drying stage. Fault-detection models can identify airflow blockage, sensor drift or abnormal heating. Optimization can reduce energy per kilogram of water removed while respecting product-quality constraints.

The limitations are equally important. Food datasets are often small, product-specific and collected under laboratory conditions. Models may interpolate well but fail when cultivar, thickness, loading or equipment scale changes. Correlated variables can produce apparently accurate but physically misleading models. Mujumdar's transport-based perspective provides an essential safeguard: AI should be constrained by mass and energy balances, validated under realistic disturbances, and interpreted in relation to known mechanisms. This principle anticipates current interest in hybrid models, digital twins and physics-informed machine learning.

7. Energy Efficiency, Low-Carbon Processing and Sustainability

Drying is energy intensive because large quantities of latent heat are required to remove water, and conventional systems often discard warm, humid exhaust. Mujumdar consistently treated energy as a design variable, promoting heat recovery, recirculation, heat pumps, staged operation, improved insulation, optimized airflow and hybrid energy delivery. Importantly, he also warned against evaluating a technology only by instantaneous drying rate. A faster process can still be inefficient if it uses high-grade energy poorly or causes rejects through nonuniform quality.

The sustainability discussion has expanded from thermal efficiency to exergy, carbon emissions, renewable energy, equipment life, food loss and lifecycle impacts. Solar, biomass, geothermal and waste-heat systems can reduce fossil energy, but their intermittency, control and capital requirements must be considered. Heat pumps can recover energy but depend on electricity source and refrigerant performance. Freeze-drying can preserve high-value nutrients and reduce downstream waste, yet may have high direct energy demand. The system boundary matters.

The 2025 review on low-carbon and future food, co-authored by Mujumdar, explicitly connects classical moisture-migration theory with lifecycle analysis, clean energy, monitoring and cost-reduction algorithms [12]. It also places drying within emerging food categories and customized production. This is a natural extension of his earlier systems philosophy: sustainability is not a single equipment label but the result of matching material, process, energy source, quality target and supply-chain function.

For industry, the most useful sustainability strategy is often a hierarchy. First, avoid unnecessary water addition and reduce mechanical dewatering loads. Second, improve uniformity so that safety does not require over-drying the entire batch. Third, recover heat and optimize humidity and airflow. Fourth, use hybrid energy selectively during rate-limiting stages. Fifth, integrate renewable or low-carbon heat where it is technically and economically appropriate. Sixth, value the avoided food loss and extended shelf life alongside direct energy consumption. Mujumdar's work supports precisely this type of whole-process reasoning.

8. Additive Manufacturing and the New Interface between Printing and Drying

Food additive manufacturing initially appeared distant from classical drying. In practice, the two are tightly connected. Extrusion printing deposits a viscoelastic food ink into a designed geometry, but the printed object may lack the mechanical strength, crispness, safety or shelf stability required for use. Baking, frying, cooling, gelation, freezing or drying become part of the manufacturing sequence. Because internal geometry is intentionally designed, post-processing can be controlled in ways that are impossible for naturally shaped foods.

The 2022 review on controlling characteristics during 3D food processing identified post-treatment as a critical barrier to wider application [13]. The printed object must retain dimensional fidelity while moisture and temperature gradients develop. The internal infill pattern, wall thickness and void fraction influence heat transfer, vapor escape, deformation and fracture. Thus, the "recipe" includes both formulation and architecture.

This concept was demonstrated experimentally in freeze-dried pumpkin snacks. By changing filling pattern and filling rate, researchers including Mujumdar produced structures with controllable shape fidelity and crispness [15]. The study exemplifies a major evolution in drying: internal structure is no longer merely a consequence of processing; it is a design variable specified before processing. Similar reasoning applies to rehydration rate, acoustic crispness, nutrient loading and mechanical accessibility for elderly or dysphagic consumers.

Broader reviews co-authored by Mujumdar examine internal design, multidimensional printing and "super reconstructed foods" whose texture, nutrition and appearance can exceed those of the original ingredient system [14,16,17]. Four-dimensional printing adds programmed change over time in response to moisture, pH, temperature, microwave energy or other stimuli. Five- and six-dimensional concepts extend tool movement and responsiveness, although many applications remain exploratory. The value of these papers lies in defining research questions: how to formulate responsive edible materials, predict deformation, ensure safety, control post-processing and scale production.

Medical and personalized foods are a particularly promising application. A 2024 review involving Mujumdar assessed 3D printing for foods for special medical purposes, including customization of nutrition, appearance and texture [18]. The technology could improve the appeal of texture-modified diets and support patient-specific composition, but regulatory validation, hygienic design, ingredient stability, consumer acceptance and cost remain substantial challenges.

Artificial intelligence provides a unifying layer. The 2024 review on AI-based additive manufacturing describes applications in model design, material selection, print-path planning, process monitoring, quality control and 4D behavior [11]. Machine learning can relate rheology and formulation to printability, use vision to detect defects, and optimize geometry and post-processing. Again, the mature engineering position is hybrid: data-driven tools should be combined with rheology, heat and mass transfer, kinetics and food-safety constraints.

The 2026 article on the role of drying in 3D/4D food printing makes this relationship explicit [19]. Drying can stabilize printed forms, generate porous textures, preserve bioactives and activate time-dependent transformations. At the same time, nonuniform shrinkage, cracking and nutrient degradation can destroy the value created during printing. Future systems will therefore co-design ink, geometry, deposition path and drying trajectory rather than optimize them sequentially.

9. Books, Book Chapters, Editorial Leadership and Knowledge Dissemination

Professor Mujumdar's impact cannot be measured solely through journal articles. The Handbook of Industrial Drying is among the most extensive references in the discipline, covering fundamentals, equipment classes, modelling, safety, energy and applications [1]. Its repeated revision has allowed generations of researchers and engineers to compare mature and emerging technologies within a common framework. The book's value is cumulative: it preserves established knowledge while creating space for new methods such as computational modelling, advanced energy sources and intensified systems.

Drying Technologies in Food Processing provided a more focused bridge to food engineering [2]. The Drying of Foods, Vegetables and Fruits series expanded access further through freely distributed, peer-reviewed volumes spanning fundamentals, properties, pretreatments, equipment, modelling, products and global research needs [3]. Other edited works and chapters address spray drying, solar drying, tropical fruits, superheated steam, heat pumps, freeze-drying and processing advances. Collectively, they provide both broad references and specialized entry points.

The open e-book initiative is especially important for researchers and students in regions with limited library budgets. Mujumdar's website lists numerous freely downloadable technical books and reports and states that he has contributed to more than 75 authored or edited books [20]. Although such figures are self-reported and should not be treated as an independent bibliometric audit, the catalogue demonstrates a sustained commitment to reducing access barriers.

His editorial leadership of Drying Technology and his role in the International Drying Symposium created an additional form of scholarly infrastructure. Journals determine which questions are visible; conferences create communities that compare methods, challenge claims and form collaborations. Through these platforms, food drying remained connected to developments in chemical engineering, materials science, energy systems, control and computational modelling. This cross-sector exposure helped prevent food drying from becoming isolated within commodity-specific traditions.

10. Global Industrial Influence, Mentorship and Research Networks

The industrial impact of an academic field such as drying is distributed and therefore difficult to attribute to one person or one patent. Mujumdar's influence is strongest through methods, trained people and design culture. Engineers use handbooks to screen dryer types, diagnose performance, estimate energy use, anticipate hazards and evaluate scale-up. Researchers trained in his network carry these methods into universities, equipment firms and food companies. Reviews help industry distinguish a promising laboratory result from a technology ready for continuous production.

Several recurring messages have direct commercial value. Uniform airflow and residence time are prerequisites for quality and safety. Mechanical dewatering and concentration should precede thermal drying where possible. The final low-rate stage often deserves a different technology or operating condition from the initial stage. Energy recovery must be assessed at plant level. Product value and quality premium determine whether vacuum or freeze-drying is justified. Sensors and models should be selected for decisions they can improve, not for novelty. Hybrid systems require integrated control rather than the independent operation of two devices.

His collaborations have been notably international. The Transport Processes Research network described on his official site includes researchers from many countries and emphasizes mentorship, joint publication and open resources [20]. In food engineering, long-standing collaborations with groups in China, Thailand, Malaysia, India, Canada and other regions have been especially productive. These relationships helped create locally relevant research on tropical produce, aquatic foods, powders, heat-pump systems, steam drying, smart processing and printed foods.

Mentorship also magnifies impact over time. Many co-authors who first worked on conventional or hybrid drying later led research programs in intelligent drying, food quality, sustainable processing and additive manufacturing. The continuity of themes across generations - transport fundamentals, product quality, energy, innovation and dissemination - suggests a school of thought rather than a single laboratory program.

11. Legacy and Future Outlook

Professor Arun S. Mujumdar's enduring legacy in food science and technology is the transformation of drying from a necessary but often empirical preservation step into a multidisciplinary platform for product and process innovation. He helped establish the language through which modern drying problems are discussed: coupled transport, internal and external resistance, quality kinetics, structure formation, hybridization, energy integration, intelligent control and system-level optimization.

His books and editorial work gave the field continuity. His collaborative reviews made emerging technologies legible to researchers and industry. His mentorship created an international community capable of moving from hot-air and heat-pump drying to microwave hybrids, AI-assisted control and multidimensional food printing without losing sight of fundamental balances. This combination of depth and adaptability explains why his work remains relevant across changing technological eras.

The next phase of food drying will likely be shaped by five converging directions. The first is physics-informed intelligence: models that combine conservation laws with machine learning and uncertainty estimation. The second is decarbonization through electrification, heat pumps, renewable heat, storage and plant-wide integration. The third is continuous quality sensing using images, spectra, aroma signals and soft sensors. The fourth is co-design of product architecture and post-processing for 3D/4D foods, plant-based structures and medical nutrition. The fifth is circular processing in which drying stabilizes by-products and converts them into ingredients rather than waste.

Mujumdar's work offers a disciplined way to pursue these opportunities. New technology should be judged by reproducible quality, specific energy consumption, carbon intensity, safety, controllability, reliability, throughput and total cost. Laboratory gains should be tested under realistic loading and variability. Digital models should remain accountable to physics. Sustainability claims should include the avoided loss and supply-chain function of the dried product. Personalized manufacturing should not compromise hygiene or affordability.

In global food processing, his greatest contribution may therefore be a way of thinking: innovate broadly, compare rigorously, integrate disciplines, communicate openly and design for the complete product-process-energy system. That legacy extends beyond any one dryer. It is embedded in how the international food-engineering community now approaches dehydration, preservation and the manufacture of future foods.

Selected timeline of the research trajectory

Period	Dominant contribution and evolution
Late 1970s-1980s	Industrial drying fundamentals, transport processes, founding of international drying forums, first Handbook era.
1990s	Expansion of dryer classifications, modelling, fluidization, energy analysis and sector-specific applications; stronger attention to biological materials.
2000s	Quality-oriented food dehydration, heat-pump and superheated-steam systems, hybrid and intensified processes, major food-processing reference books.
2010s	Global collaborative reviews on fruits, vegetables and aquatic products; pretreatments, ultrasound, microwave hybrids, computer vision and AI.
2020s	Low-carbon drying, ready-to-eat and medical foods, 3D/4D printing, internal-structure design, AI-assisted additive manufacturing and integrated post-processing.

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Closing assessment. Professor Mujumdar’s food-science legacy lies in uniting rigorous transport engineering with the practical goals of preservation, quality, sustainability and manufacturability. His work has helped ensure that drying remains a central - and continually reinvented - technology for the global food system.